Connecting Neutrinoless double beta decay to colliders. Or not.

Amherst, Massachusetts
July 2017

Michael Graesser (Los Alamos)

based on:

MG, arXiv:1606.04549, submitted to JHEP
V. Cirigliano, W. Dekens, MG, E. Mereghetti, (PLB 2017, 1701.01443)
V. Cirigliano, W. Dekens, J. de Vries, MG, E. Mereghetti, (1707/08.zzzz)

Neutrinoless double beta decay and TeV* scale physics

Motivation

Neutrinos have mass and search is on to discover the nature of their mass.

Ongoing or future experiments may detect a "neutrinoless double beta decay" signal.

Such a signal arises when neutrino masses violate lepton number (i.e., Majorana)

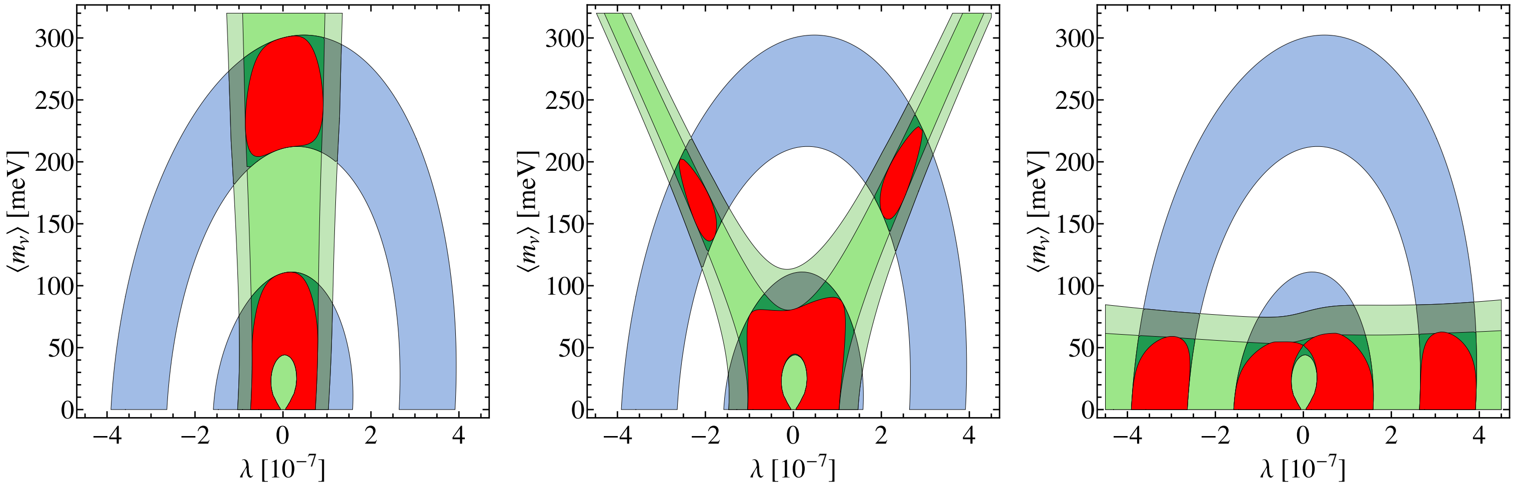
Question: is that the correct interpretation of such a signal?

Are there other (new physics scenario) interpretations?

New physics scenarios for neutrinoless double beta decay

Should a $\Delta L=2$ signal be detected, such exotic possibilities should be excluded before concluding that effect is due to Majorana neutrino exchange

Resolving competing explanations may need a next-generation detector reconstructing both electron kinematics (e.g. NEXT, SuperNEMO)



(a) (b) (c)

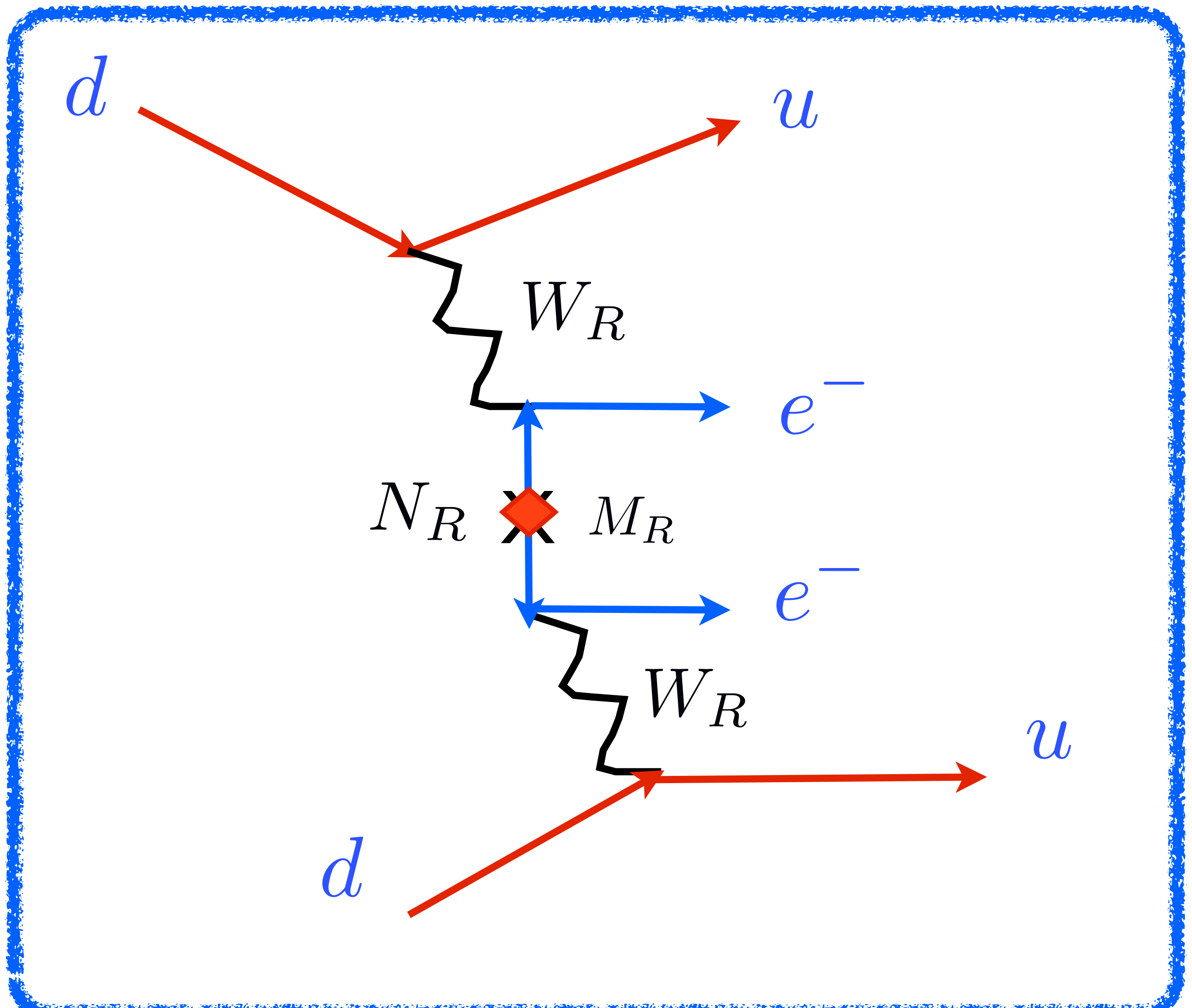
Comparison SuperNEMO sensitivity to various admixtures of W_R contribution (0%, 30%, 100%). Figure from Arnold et. al. (SuperNEMO, 2010)

- If hierarchy is "normal", then planned 0nubb have no chance of detecting Standard Model Majorana neutrinos (outside of the quasi-degenerate region)

- In such a circumstance, only hope is for exotic scenarios

BSM contributions to neutrinoless beta decay:

Left-Right symmetric model



- new electroweak gauge bosons couple to right-handed currents
- new right-handed or "sterile" neutrinos, electroweak partners of Standard Model right-handed electron
- possibility for type-II see-saw at TeV scale

$$\mathcal{L}_Y = \frac{1}{2}\ell_L \frac{M_{\nu_L}}{\langle\Delta_L\rangle}\Delta_L \ell_L + \frac{1}{2}\ell_R \frac{M_{\nu_R}}{\langle\Delta_R\rangle}\Delta_R \ell_R + \text{h.c.}$$

- Assuming a type-II see-saw, C invariance leads

$$M_{\nu_R}/\langle\Delta_R\rangle = M^*_{\nu_L}/\langle\Delta_L\rangle^* \quad \text{or} \quad m_N \propto m_\nu$$

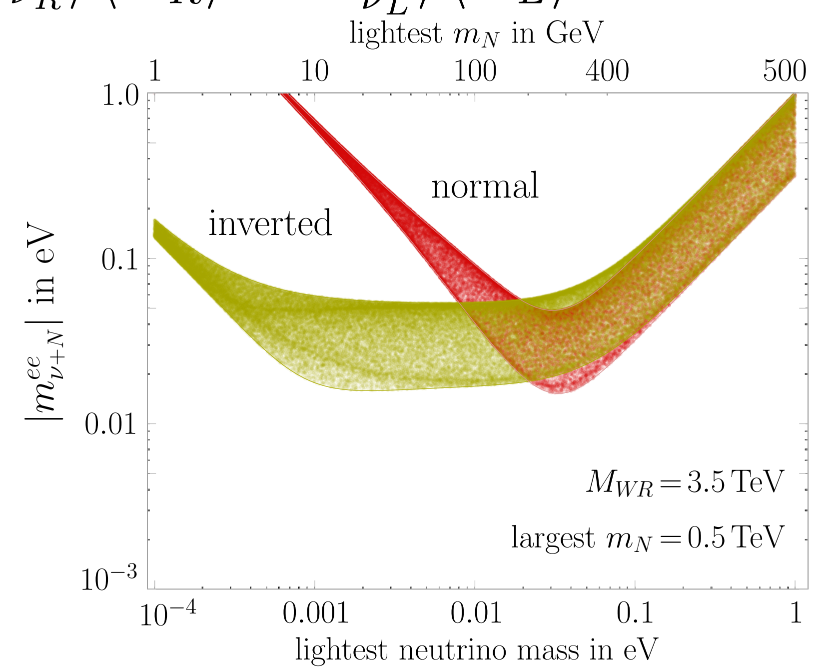
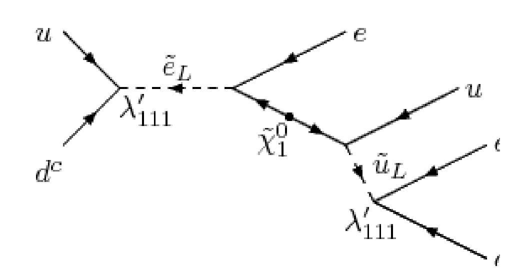


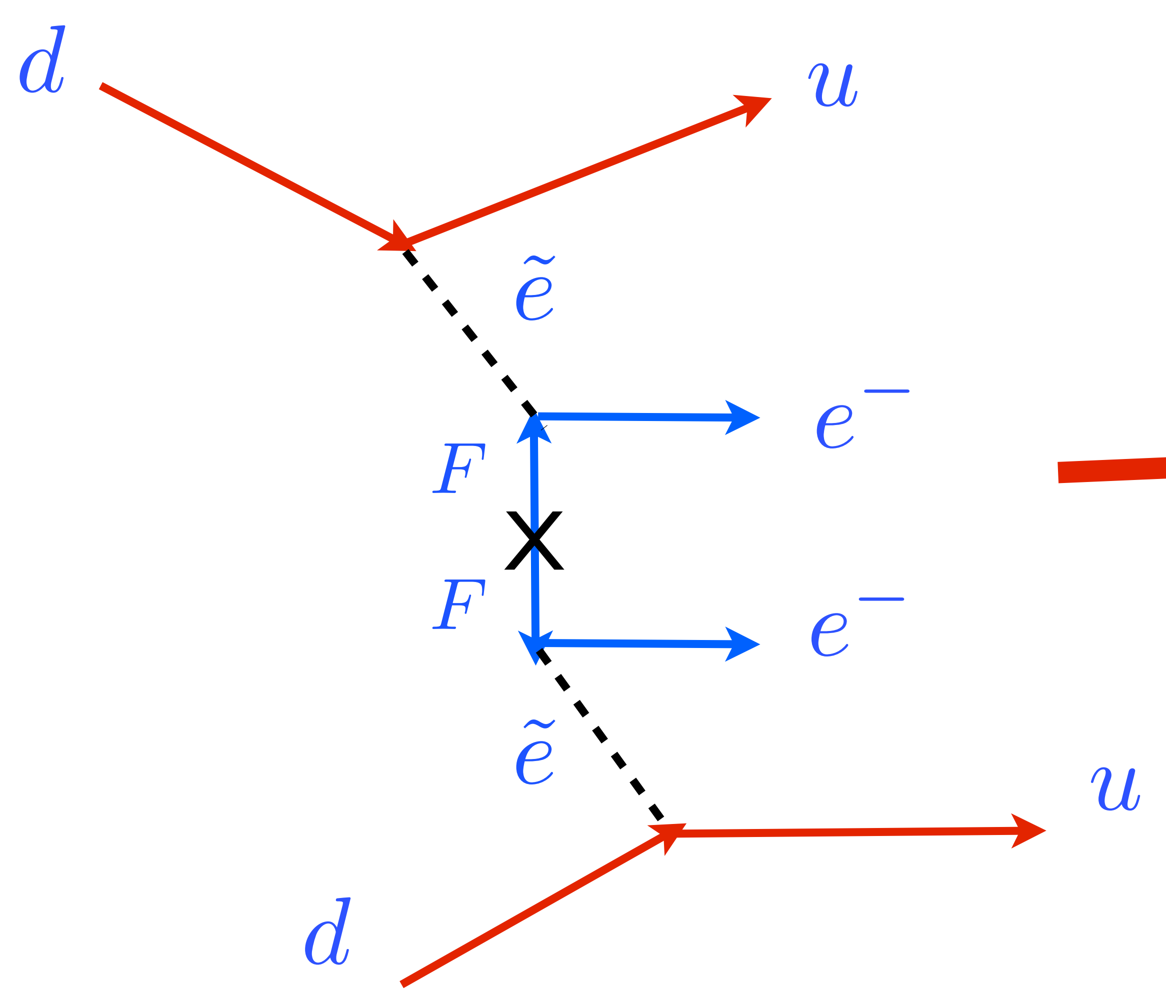
Figure from Tello, Nemevsek, Nesti, Senjanovic and Vissani, 2011

BSM contributions to neutrinoless beta decay:

R-parity violation inspired



- see also e.g. Deppisch, Hirsch, Pas, 2012



- new charged scalar leptons ("sleptons")
- new electroweak partners of the electron
- generate different contact operator at low energies

$$\mathcal{L}^{\rm eff}_{\rm LNV} = \frac{C_1}{\Lambda^5}\mathcal{O}_1 + {\rm h.c.} \quad , \quad \mathcal{O}_1 = \bar{Q}\tau^+ d\bar{Q}\tau^+ d\bar{L}L^C$$

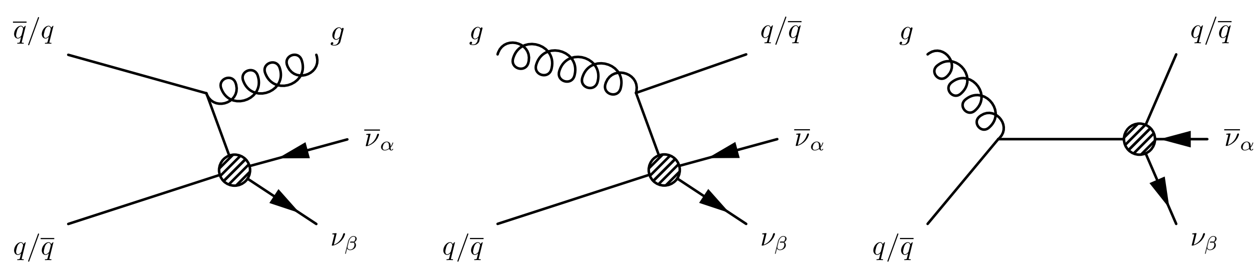
see e.g. M. Ramsey-Musolf, T. Peng and P. Winslow, 2015 for thorough LHC collider phenomenology analysis (and see M. Ramsey Musolf's talk)

- R-M P W include leading 2 pion interactions and RGE analysis, backgrounds, detector sim.
- and determine signal acceptances - very model-dependent

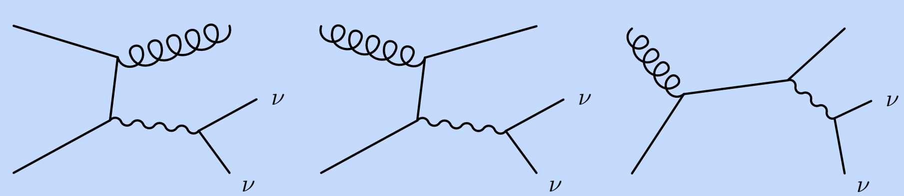
Sidebar: Acceptance is model-dependent

E.g. Monojet bounds on Non-standard Neutrino Interactions

(A. Friedland, MG, I. Shoemaker, L. Vecchi, '12)

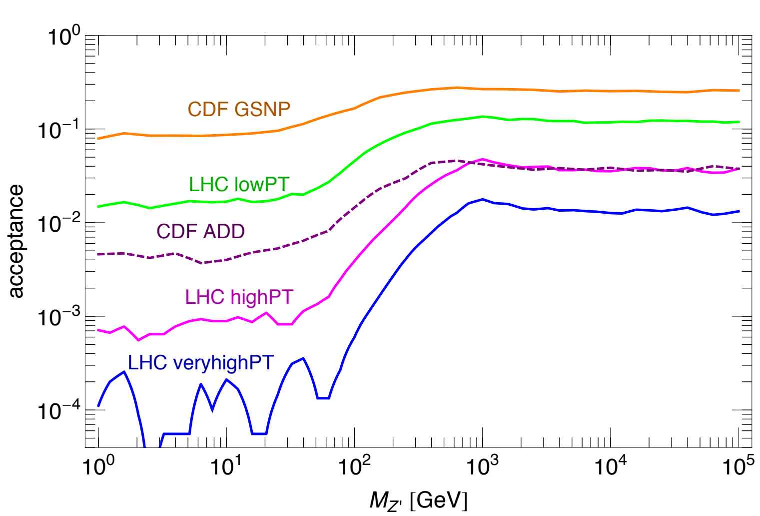


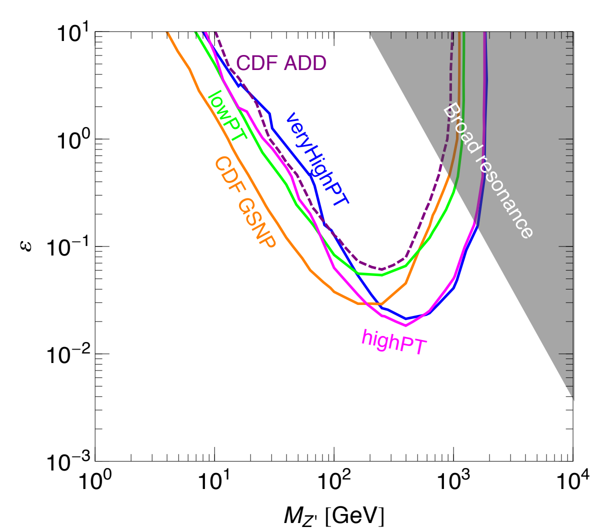
Z' model



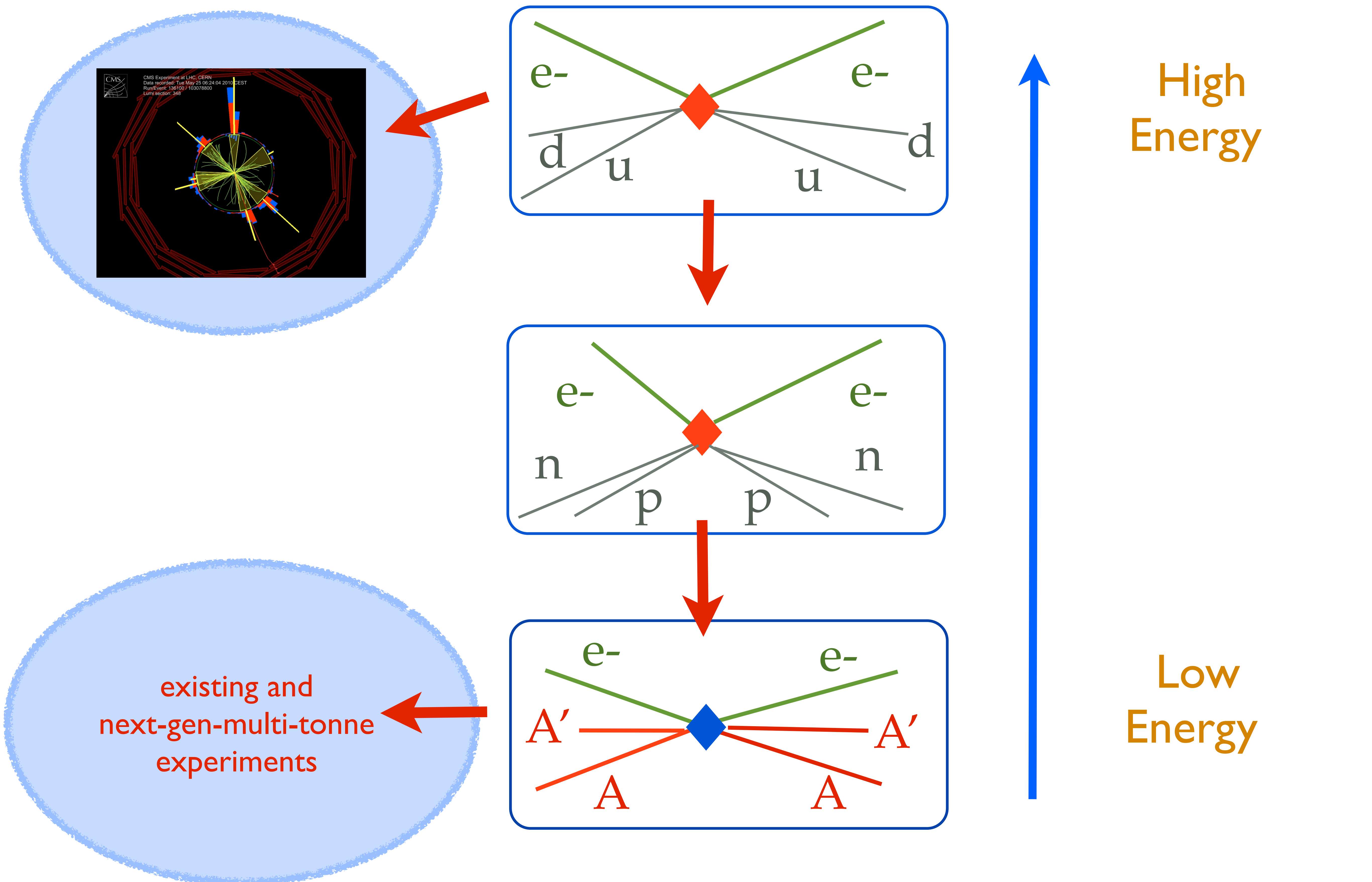
For fixed cuts, weaker limit for lighter mediator

- can't just use reported sigma*BR, common to many 0nubb <-> LHC comparisons
- need to determine acceptance for your favorite model



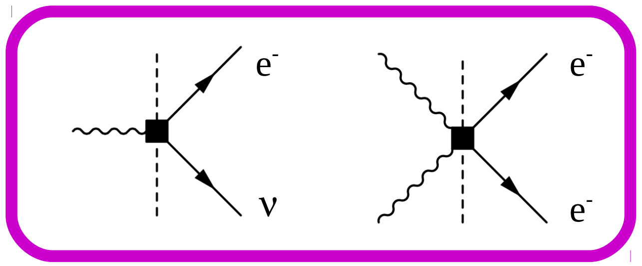


BSM contributions to neutrinoless beta decay

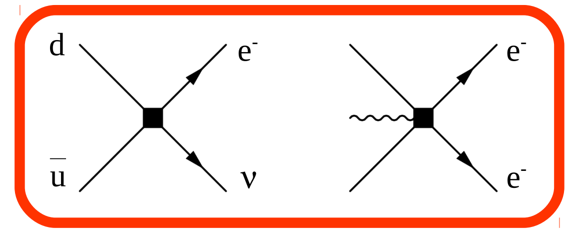


Dimension 7 ΔL=2 LNV operators

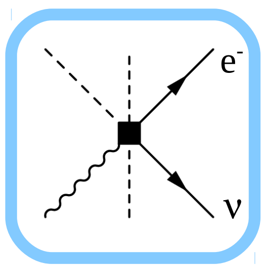
Nice figures from E. Mereghetti, INT seminar 2017



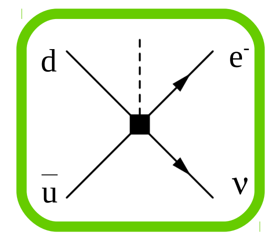
$$\varepsilon_{ij}\varepsilon_{mn}\, L_i^T C (D_\mu L)_j\, H_m (D^\mu H)_n$$



$$\varepsilon_{ij}\, \bar{d}\gamma_\mu u\, L_i^T C (D^\mu L)_j$$

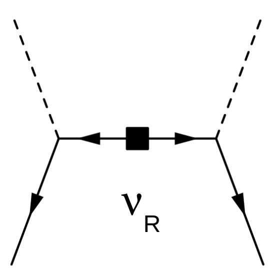


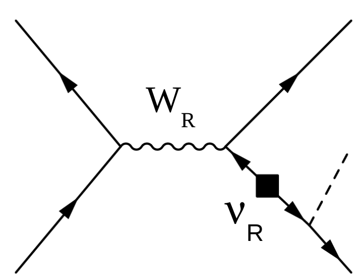
$$\varepsilon_{ij}\varepsilon_{mn}\, L_i^T C\gamma_\mu e\, H_j H_m (D^\mu H)_n$$

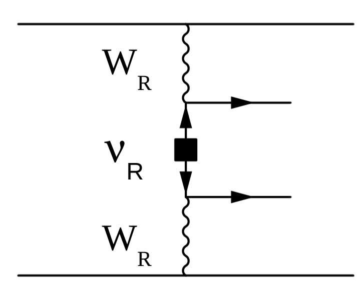


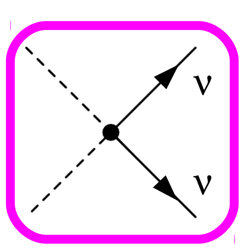
$$\varepsilon_{ij}\varepsilon_{mn} \bar{d} L_i\, Q_j^T C L_m\, H_n$$

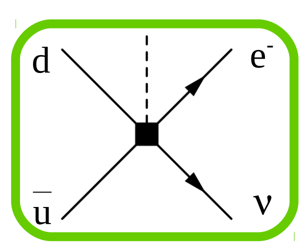
Sample dimension -5,-7,-9 ΔL=2 LNV operators

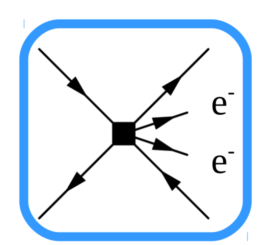






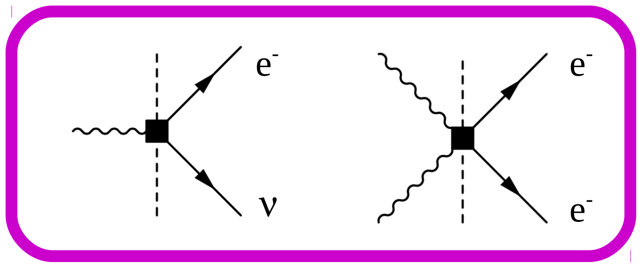






Dimension 7 ΔL=2 LNV operators

Nice figures from E. Mereghetti, INT seminar 2017



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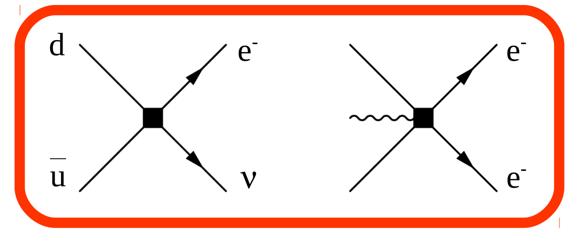

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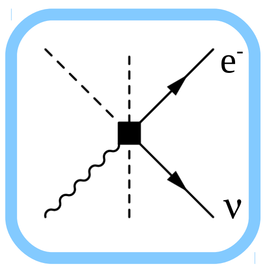
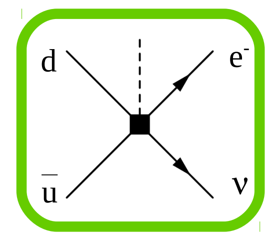
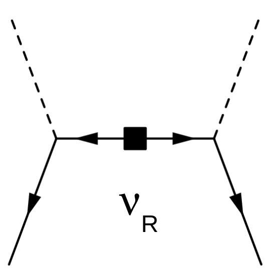


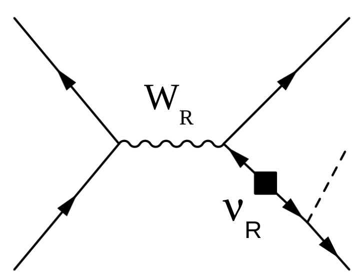
$$\varepsilon_{ij}\varepsilon_{mn}\, L_i^T C\gamma_\mu e\, H_j H_m (D^\mu H)_n$$

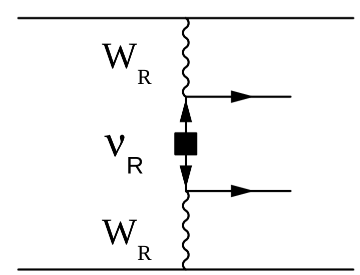


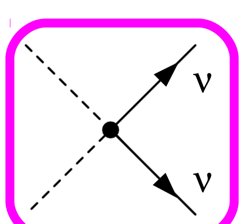
$$\varepsilon_{ij}\varepsilon_{mn}\bar{d} L_i\, Q_j^T C L_m\, H_n$$

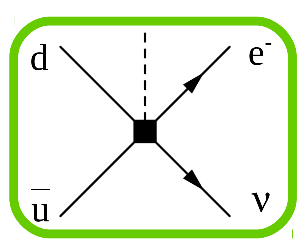
Sample dimension -5,-7,-9 ΔL=2 LNV operators

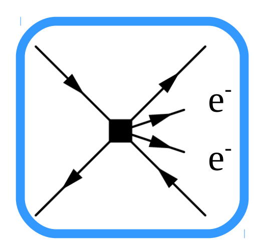








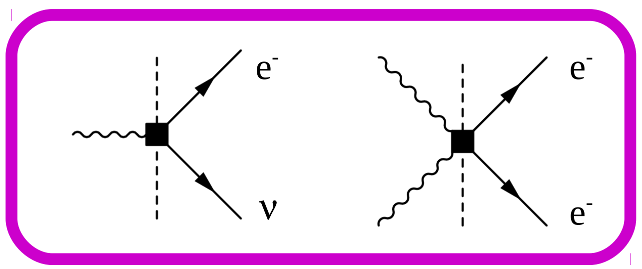




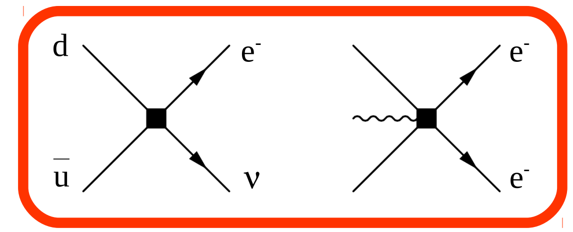
Part 1

Dimension 7 ΔL=2 LNV operators

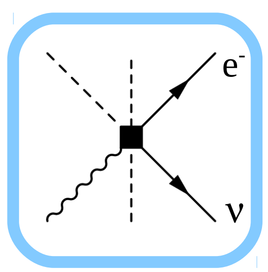
Nice figures from E. Mereghetti, INT seminar 2017



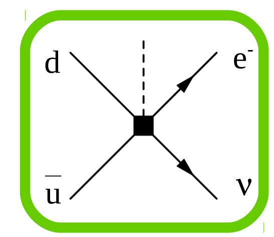
$\varepsilon_{ij}\varepsilon_{mn} L_i^T C (D_\mu L)_j H_m (D^\mu H)_n$



$\varepsilon_{ij}\bar{d}\gamma_\mu u L_i^T C (D^\mu L)_j$

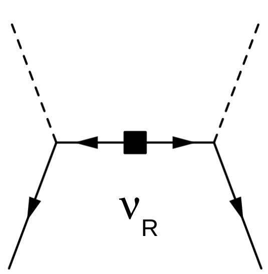


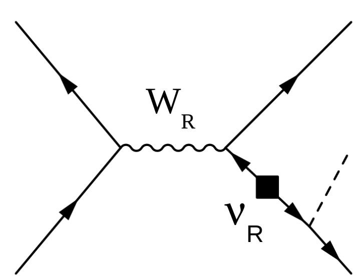
$\varepsilon_{ij}\varepsilon_{mn} L_i^T C\gamma_\mu e H_j H_m (D^\mu H)_n$

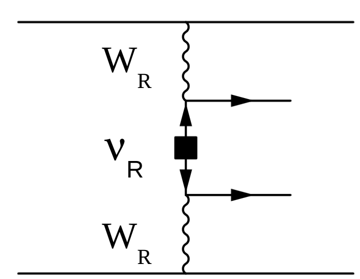


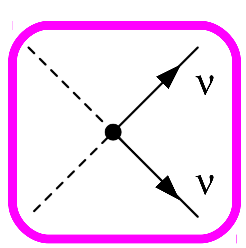
$\varepsilon_{ij}\varepsilon_{mn}\bar{d} L_i Q_j^T C L_m H_n$

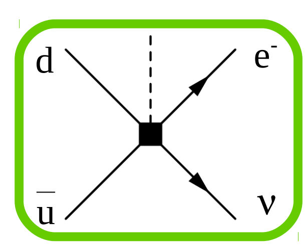
Sample dimension -5,-7,-9 ΔL=2 LNV operators

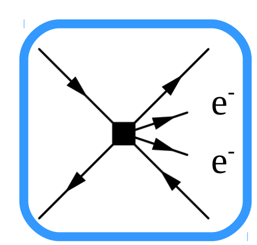












Part 2

Disclaimer/Philosophy for new physics scenarios for neutrinoless double beta decay

- Will use effective field theory to study connection between high-energy (below $\Delta L=2$ mass scale) and 0nubb experiments (low-energy)

- Plug-in favorite UV model to matching condition of Wilson coefficients

- But it would be nice if favorite UV model had some other compelling feature (Feynman)

- Theoretical inputs:
  - (pQCD) anomalous dimensions of operators
  - lattice inputs to QCD matrix elements (becoming increasingly under control)
  - nuclear matrix elements of nucleon operators

- Neutrino mass generation may be sub-dominant to 0nubb experimental signal (see Michael Ramsey-Musolf's talk)

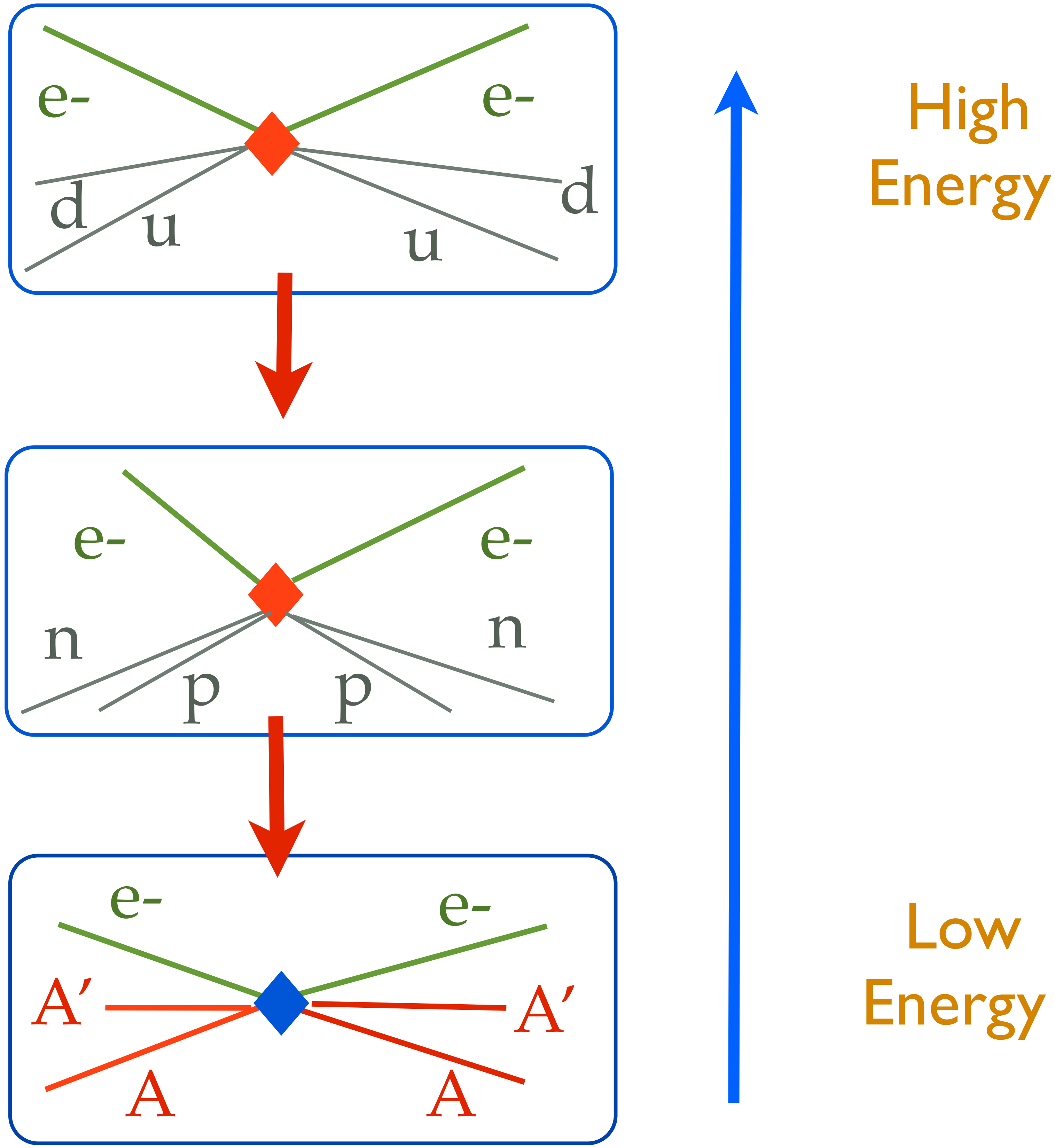
BSM contributions to neutrinoless beta decay

Model -> gauge
invariant operators

RG evolution
Match at EW scale
RG evolution to QCD scale

Match onto chiral EFT
(lattice input for LEC)

Neutrino potentials,
nuclear matrix element



Effective field theory analysis of BSM contributions to neutrinoless double beta decay

- new particles generating ΔL=2 processes have masses in multi-TeV scale.
- 0nubb process generated at very short distances.
- Leading effects of such TeV scale physics can be described by series of ΔL=2 violating operators involving only quarks and leptons

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_{\nu,M} + \sum_{i,d>4} \frac{c_i^d}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

e.g., $dd \to uue^-e^-$

(collider signal:
Keung, Senjanovic, PRL, 1983)

At "low energy" - ie QCD scale - there are a number of "short distance" operators that contribute to neutrinoless double beta decay (Prezeau, Ramsey-Musolf and Vogel (PRD, 68, 2003))

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^5_{\rm LNV}} \left[\sum_{i={\rm scalar}} \left(c_{i,S}\, \bar{e} e^c + c'_{i,S}\, \bar{e}\gamma_5 e^c \right) O_i \; + \; \bar{e}\gamma_\mu \gamma_5 e^c \sum_{i={\rm vector}} c_{i,V}\, O_i^\mu \right]$$

What is a minimal basis (MG, arXiv:1606.04549) ?

- leading ΔL=2 operator with two charged leptons has a minimum of 4 quarks, in other words, dimension 9

- For ΔL=2 phenomenology (e.g., 0nubb decay rates) need to know a minimal basis of operators, the set of relevant operators that cannot be reduced by Fierz operators

- Electromagnetic invariance: 24 (compared to 14=2*5+4 in prior literature):
  8 scalar and 8 vector 4-quark operators

- Electroweak invariance: If scale Λ of ΔL=2 violating physics is much larger than the electroweak scale, effect of ΔL=2 physics appears as a series of higher dimension operators invariant under the full Standard Model gauge symmetry

- If color + electroweak invariance is imposed, then 11 operators at LO in v/Λ: 7 scalar and 4 vector

- At hadron colliders, if E << Λ, then collider only probing (color + electroweak invariant) ΔL=2 contact operators. In this "contact limit" can classify their experimental signatures.

Electroweak invariant dimension 9 operators:
collider signatures

operator	content	hadron collider signatures: same-sign dilepton	hadron collider signatures: e+MET	hadron collider signatures: dijet+ MET	Low Energy
dimension 9					
LM1	$i\sigma^{(2)}_{ab}(\overline{Q}_a\gamma^\mu Q_c)(\overline{u}_R\gamma_\mu d_R)(\overline{\ell}_b\ell^C_c)$	√	√	√	$\mathcal{O}_{1LR}\otimes(LL)$
LM2	$i\sigma^{(2)}_{ab}(\overline{Q}_a\gamma^\mu\lambda^A Q_c)(\overline{u}_R\gamma_\mu\lambda^A d_R)(\overline{\ell}_b\ell^C_c)$	√	√	√	$\mathcal{O}^\lambda_{1LR}\otimes(LL)$
LM3	$(\overline{u}_R Q_a)(\overline{u}_R Q_b)(\overline{\ell}_a\ell^C_b)$	√	√	√	$\mathcal{O}_{2RL}\otimes(LL)$
LM4	$(\overline{u}_R\lambda^A Q_a)(\overline{u}_R\lambda^A Q_b)(\overline{\ell}_a\ell^C_b)$	√	√	√	$\mathcal{O}^\lambda_{2RL}\otimes(LL)$
LM5	$i\sigma^{(2)}_{ab}i\sigma^{(2)}_{cd}(\overline{Q}_a d_R)(\overline{Q}_c d_R)(\overline{\ell}_b\ell^C_d)$	√	√	√	$\mathcal{O}_{2LR}\otimes(LL)$
LM6	$i\sigma^{(2)}_{ab}i\sigma^{(2)}_{cd}(\overline{Q}_a\lambda^A d_R)(\overline{Q}_c\lambda^A d_R)(\overline{\ell}_b\ell^C_d)$	√	√	√	$\mathcal{O}^\lambda_{2LR}\otimes(LL)$
LM7	$(\overline{u}_R\gamma^\mu d_R)(\overline{u}_R\gamma_\mu d_R)(\overline{e}_R e^C_R)$	√	☹	☹	$\mathcal{O}_{3R}\otimes(RR)$
LM8	$(\overline{u}_R\gamma^\mu d_R)i\sigma^{(2)}_{ab}(\overline{Q}_a d_R)(\overline{\ell}_b\gamma_\mu e^C_R)$	√	√	☹	$\mathcal{O}^\mu_{RRLR}\otimes(LR)$
LM9	$(\overline{u}_R\gamma^\mu\lambda^A d_R)i\sigma^{(2)}_{ab}(\overline{Q}_a\lambda^A d_R)(\overline{\ell}_b\gamma_\mu e^C_R)$	√	√	☹	$\mathcal{O}^{\lambda\mu}_{RRLR}\otimes(LR)$
LM10	$(\overline{u}_R\gamma^\mu d_R)(\overline{u}_R Q_a)(\overline{\ell}_a\gamma_\mu e^C_R)$	√	√	☹	$\mathcal{O}^\mu_{RRRL}\otimes(LR)$
LM11	$(\overline{u}_R\gamma^\mu\lambda^A d_R)(\overline{u}_R\lambda^A Q_a)(\overline{\ell}_a\gamma_\mu e^C_R)$	√	√	☹	$\mathcal{O}^{\lambda\mu}_{RRRL}\otimes(LR)$

scalar 4-quark operators (7) (LM1–LM7)

vector 4-quark operators (4) (LM8–LM11)

↔ RPV-inspired theory (LM6)

↔ LR symmetric theory (LM7)

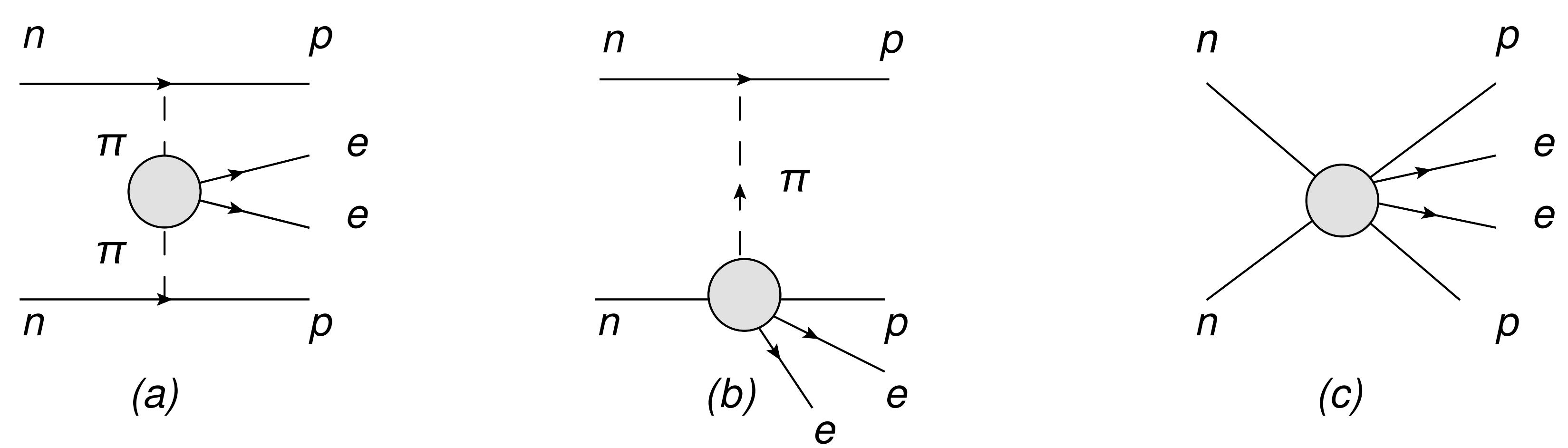
Table from MG, arXiv:1606.04549

- Set up systematic formalism for χPT operators in low-energy effective field theory
- Applied general formalism to identify which operators contribute at LO to eeππ interactions (i.e., which ops. in χPT dominate ΔL=2 amplitude over effects of eeπNN and eeNNNN interactions)

Effective field theory analysis of BSM contributions to neutrinoless double beta decay: Weinberg power counting

• Quarks couple to everything, so expect 4 quark operator to generate many multi-hadron interactions

• Two pion interaction important (Faessler, S. Kovalenko, F. Simkovic, and J. Schwieger, 1996; Prezeau, Ramsey-Musolf and Vogel (PRD, 68, 2003)) but not consistently implemented in other literature

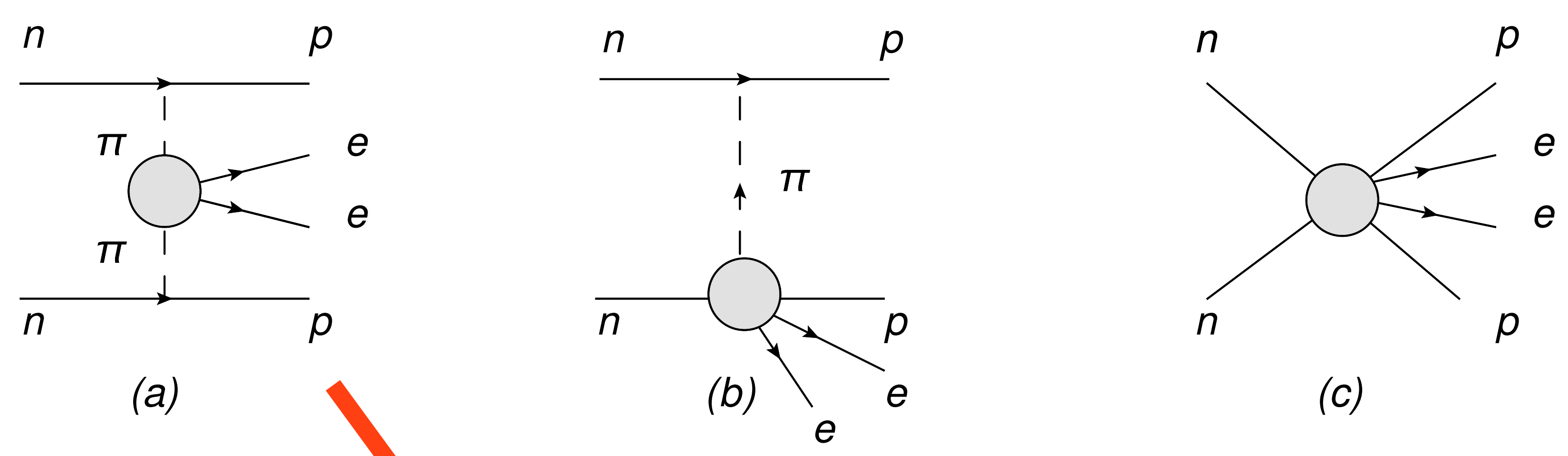


$O(q^{-2+\Delta_{\mathcal{O}}(\pi\pi)})$ $O(q^{-1+\Delta_{\mathcal{O}}(\pi NN)})$ $O(q^{0+\Delta_{\mathcal{O}}(NNNN)})$

• A number of analyses comparing LHC projections and 0nubb limits only include 4-nucleon interactions, "conservatively" suppressing limits from 0nubb experiments (unfairly promotes the competitiveness of the LHC)

• Here power counting is for free field theory only - need to insert inside a nucleus and test power-counting

Effective field theory analysis of BSM contributions to neutrinoless double beta decay: Estimate of long-distance pion exchange



$$O(q^{-2+\Delta_{\mathcal{O}}(\pi\pi)})$$

$$\mathcal{A}_{\pi\pi} \simeq \frac{1}{\Lambda_{\rm LNV}^5}\frac{M_{\langle\pi^+|O_i|\pi^-\rangle}}{f_\pi^2 q^2} \sim 10^2\frac{1}{\Lambda_{\rm LNV}^5}\frac{M_{\langle O_i\rangle}}{10^{-2}}\frac{(100\ {\rm MeV})^4}{f_\pi^2 q^2}$$

$$\mathcal{A}_{\rm SM} \simeq G_F^2\frac{m_{\beta\beta}}{q^2}$$

chiral PT estimate: $M_{\langle O_i\rangle} \sim 10^{-2}\ (O_{2,3,4,5}, O'_{2,3})$

Effective field theory analysis of BSM contributions to neutrinoless double beta decay (MG, arXiv:1606.04549)

General $\Delta L=2$ 4-quark scalar operator (following Savage 1999)

$$\mathcal{O} = T^{ab}_{cd}(\overline{q}^c \Gamma q_a)(\overline{q}^d \Gamma' q_b), \; T^{ab}_{cd} = (\tau^+)_c{}^a (\tau^+)_d{}^b$$

Transform T such that O is formally chirally invariant

$$\begin{aligned} q_L &\rightarrow Lq, \; q_R \rightarrow R q_R, \\ T &\rightarrow T \otimes X_1 \otimes X_2 \otimes X_3 \otimes X_4, \; X_i \in \{L, R, L^\dagger, R^\dagger\} \end{aligned}$$

Construct pion and nucleon operators in chiral theory such that they are formally chirally invariant

$$T^{ab}_{cd} \tilde{\mathcal{O}}^{cd}_{ab}(\pi, N)$$

Effective field theory analysis of BSM contributions to neutrinoless double beta decay: Weinberg power counting

With $\xi = \mathrm{Exp}[\pi \cdot \tau / 2F_\pi],\ \xi \to L\xi U^\dagger = U\xi R^\dagger,\ N \to UN$

Construct "proto-O" out of products of ξ's such that

$$(proto - \tilde{O}) \quad \to \quad (proto - \tilde{O}) \otimes Y_1 \otimes Y_2 \otimes Y_3 \otimes Y_4,\ Y_i \in \{U, U^\dagger\}$$

To construct invariants

- only pions: takes all possible traces
- pions and two nucleons: multiply by two N fields in all possible ways, take all possible traces
- Four nucleons: multiply in by 4 nucleon fields in all possible ways
- can also generate new operators involving higher chiral order using chiral transformation properties of quark mass and covariant derivative

Example: Operators from W_R exchange (Left-right-symmetric model)

$$\mathcal{O}_{3R} \equiv (\overline{q}_R \gamma^\mu \tau^+ q_R)(\overline{q}_R \gamma_\mu \tau^+ q_R)$$

$$T^{ab}_{cd} \to T^{\alpha\beta}_{\rho\sigma} R^\rho_c R^\sigma_d R^{\dagger a}_\alpha R^{\dagger b}_\beta$$

$$proto - \tilde{O}_{3R} = T^{ab}_{cd} \xi^{\dagger i}_a \xi^{\dagger j}_b \xi^c_k \xi^d_l$$

To construct invariants

- only pions: takes all possible traces -> all vanish (in this example)
- Four nucleons: multiply in by 4 nucleon fields in all possible ways -> non-vanishing operator involving 4 nucleons
- can also generate new operators involving higher chiral order using chiral transformation properties of quark mass and covariant derivative -> Find a number of single and double trace operators, e.g.

$$\mathrm{tr}(\mathcal{D}^\mu \xi \tau^+ \mathcal{D}_\mu \xi^\dagger \xi \tau^+ \xi^\dagger)$$

For this operator, expect first non-vanishing two-pion matrix element at NLO -- which we confirmed using chiral SU(3) -- and first non-vanishing 4 nucleon matrix element at LO

Electroweak invariant dimension 9 operators:

two-pion couplings

operator	content	hadron collider signatures			Low Energy	χPT ($\pi\pi$)
		same-sign dilepton	e+MET	dijet+ MET		
dimension 9						
LM1	$i\sigma^{(2)}_{ab}(\overline{Q}_a\gamma^\mu Q_c)(\overline{u}_R\gamma_\mu d_R)(\overline{\ell}_b\ell^C_c)$	$\surd$	$\surd$	$\surd$	$\mathcal{O}_{1LR}\otimes(LL)$	LO
LM2	$i\sigma^{(2)}_{ab}(\overline{Q}_a\gamma^\mu\lambda^A Q_c)(\overline{u}_R\gamma_\mu\lambda^A d_R)(\overline{\ell}_b\ell^C_c)$	$\surd$	$\surd$	$\surd$	$\mathcal{O}^\lambda_{1LR}\otimes(LL)$	LO
LM3	$(\overline{u}_R Q_a)(\overline{u}_R Q_b)(\overline{\ell}_a\ell^C_b)$	$\surd$	$\surd$	$\surd$	$\mathcal{O}_{2RL}\otimes(LL)$	LO
LM4	$(\overline{u}_R\lambda^A Q_a)(\overline{u}_R\lambda^A Q_b)(\overline{\ell}_a\ell^C_b)$	$\surd$	$\surd$	$\surd$	$\mathcal{O}^\lambda_{2RL}\otimes(LL)$	LO
LM5	$i\sigma^{(2)}_{ab}i\sigma^{(2)}_{cd}(\overline{Q}_a d_R)(\overline{Q}_c d_R)(\overline{\ell}_b\ell^C_d)$	$\surd$	$\surd$	$\surd$	$\mathcal{O}_{2LR}\otimes(LL)$	LO
LM6	$i\sigma^{(2)}_{ab}i\sigma^{(2)}_{cd}(\overline{Q}_a\lambda^A d_R)(\overline{Q}_c\lambda^A d_R)(\overline{\ell}_b\ell^C_d)$	$\surd$	$\surd$	$\surd$	$\mathcal{O}^\lambda_{2LR}\otimes(LL)$	LO
LM7	$(\overline{u}_R\gamma^\mu d_R)(\overline{u}_R\gamma_\mu d_R)(\overline{e}_R e^C_R)$	$\surd$	$\ddot{\frown}$	$\ddot{\frown}$	$\mathcal{O}_{3R}\otimes(RR)$	NNLO
LM8	$(\overline{u}_R\gamma^\mu d_R)i\sigma^{(2)}_{ab}(\overline{Q}_a d_R)(\overline{\ell}_b\gamma_\mu e^C_R)$	$\surd$	$\surd$	$\ddot{\frown}$	$\mathcal{O}^\mu_{RRLR}\otimes(LR)$	-
LM9	$(\overline{u}_R\gamma^\mu\lambda^A d_R)i\sigma^{(2)}_{ab}(\overline{Q}_a\lambda^A d_R)(\overline{\ell}_b\gamma_\mu e^C_R)$	$\surd$	$\surd$	$\ddot{\frown}$	$\mathcal{O}^{\lambda\mu}_{RRLR}\otimes(LR)$	-
LM10	$(\overline{u}_R\gamma^\mu d_R)(\overline{u}_R Q_a)(\overline{\ell}_a\gamma_\mu e^C_R)$	$\surd$	$\surd$	$\ddot{\frown}$	$\mathcal{O}^\mu_{RRRL}\otimes(LR)$	-
LM11	$(\overline{u}_R\gamma^\mu\lambda^A d_R)(\overline{u}_R\lambda^A Q_a)(\overline{\ell}_a\gamma_\mu e^C_R)$	$\surd$	$\surd$	$\ddot{\frown}$	$\mathcal{O}^{\lambda\mu}_{RRRL}\otimes(LR)$	-

7 "scalar" quark operators

4 "vector" quark operators

↔ RPV-inspired theory

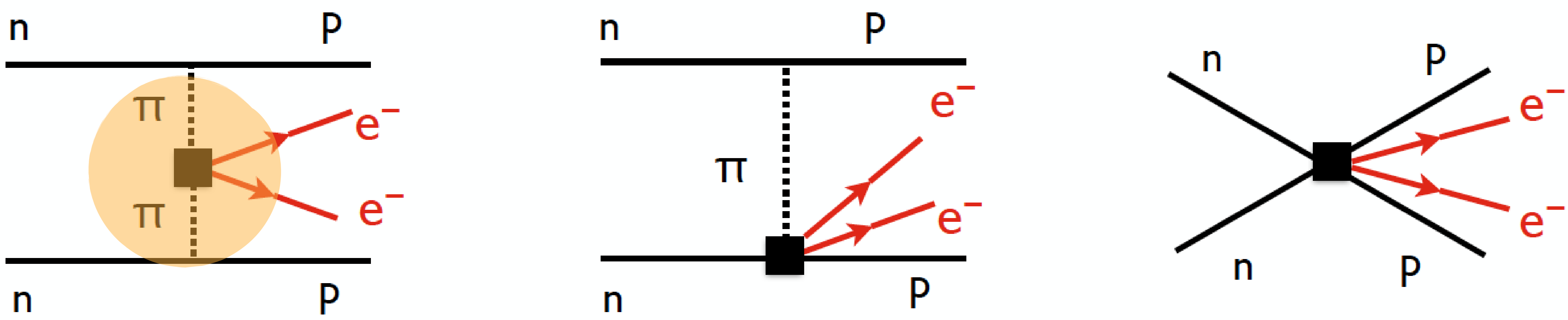
↔ LR symmetric theory

Table from MG, arXiv:1606.04549

- Only one pair of scalar operators suppressed in chiPT counting (O_1,O'_1)
- Confirm two-pion interactions from vector operators suppressed by electron mass through NNLO (Prezeau, Ramsey-Musolf, Vogel)

Effective chiral field theory analysis of BSM contributions to neutrinoless double beta decay: two pion matrix elements

V. Cirigliano, W. Dekens, MG, E. Mereghetti, 1701.01443, PLB 2017



From the minimal basis, 8 scalar quark operators:

$$
\begin{aligned}
O_1 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \; \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta \\
O_2 &= \bar{q}_R^\alpha \tau^+ q_L^\alpha \; \bar{q}_R^\beta \tau^+ q_L^\beta \\
O_3 &= \bar{q}_R^\alpha \tau^+ q_L^\beta \; \bar{q}_R^\beta \tau^+ q_L^\alpha \\
O_4 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta \\
O_5 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\beta \; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\alpha
\end{aligned}
$$

$$+ \, O'_{1,2,3} \text{ from } L \leftrightarrow R \text{ on } O_{1,2,3}$$

For 0nubb phenomenology, need matrix elements

$$\langle \pi^+ | O_i | \pi^- \rangle$$

Two pion matrix elements

- O_1, O_1' two pion matrix element determined by M. Savage (1999) using chiral SU(3) symmetry to relate $\pi\pi$ amplitude to $\Delta I=3/2$ K-> $\pi\pi$ decay

- we were able to extend Savage's analysis to all such operators, by relating two pion matrix elements to those involving $\Delta S=1, 2$ matrix elements which are now accurately computed on the lattice

- preliminary lattice computations exist for two pion matrix elements (Nicholson et. al., 2015)

Two pion matrix elements

- 4 quark operators belong to irreducible representations of $SU(3)_L \times SU(3)_R$

$$q_{L,R} \quad \sim \quad \mathbf{3_{L,R}}$$

$$\begin{aligned}
O_1 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \; \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta \\
O_2 &= \bar{q}_R^\alpha \tau^+ q_L^\alpha \; \bar{q}_R^\beta \tau^+ q_L^\beta \\
O_3 &= \bar{q}_R^\alpha \tau^+ q_L^\beta \; \bar{q}_R^\beta \tau^+ q_L^\alpha \\
O_4 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta \\
O_5 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\beta \; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\alpha
\end{aligned}$$

$SU(3)_L \times SU(3)_R$ →

$$O_1 \sim \mathbf{27_L} \otimes \mathbf{1_R}$$

$$O_{2,3} \sim \mathbf{6_L} \otimes \mathbf{\overline{6}_R}$$

$$O_{4,5} \sim \mathbf{8_L} \otimes \mathbf{8_R}$$

- + $O'_{1,2,3}$ by L <--> R from $O_{1,2,3}$; by parity same QCD matrix element

- $O_1 \sim (\overline{u}_L d_L)(\overline{u}_L d_L) \quad \rightarrow \quad I = (2_L, 0_R)$

  $$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} + \mathbf{10} + \mathbf{10} + \mathbf{8} + \mathbf{8} + \mathbf{1}$$

  and only 27 contains I=2 ⟶ $27_L \otimes 1_R$

- $O_{2,3} \sim (\overline{u}_R d_L)(\overline{u}_R d_L) \quad \rightarrow \quad I = (1_L, 1_R)$

  and contains "symmetric component" ⟶ $6_L \otimes \overline{6}_R$

Chiral perturbation theory

First consider $O_{2,3,4,5}$+ $O'_{2,3,4,5}$, then return to O_1, O_1'

$$U = \exp\left(\frac{\sqrt{2} i\pi}{F_0}\right), \qquad \pi = \begin{pmatrix} \frac{\pi_3}{\sqrt{2}} + \frac{\pi_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi_3}{\sqrt{2}} + \frac{\pi_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\pi_8 \end{pmatrix} \qquad U \rightarrow L U R^\dagger$$

$$\begin{aligned} O_{4,5} &= \overline{q}_L T^a \gamma^\mu q_L \; \overline{q}_R T^b \gamma_\mu q_R \\ T^a &\rightarrow L T^a L^\dagger \\ T^b &\rightarrow R T^b R^\dagger \end{aligned}$$

Only $\mathrm{Tr}\; T^a U T^b U^\dagger$ is formally invariant

Chiral perturbation theory

$$U = \exp\left(\frac{\sqrt{2}i\pi}{F_0}\right), \qquad \pi = \begin{pmatrix} \frac{\pi_3}{\sqrt{2}} + \frac{\pi_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi_3}{\sqrt{2}} + \frac{\pi_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\pi_8 \end{pmatrix} \qquad U \rightarrow LUR^\dagger$$

$$O_{2,3} = \bar{q}_R T^a q_L \;\; \bar{q}_R T^b q_L$$

$$T^{a,b} \rightarrow RT^{a,b}L^\dagger$$

Here there are two formal invariants

$\mathrm{Tr}\ T^a U T^b U$ and $\mathrm{Tr}\ T^a U$

Specific linear combination keeps the 6 and projects out the 3*

Matching quark operators onto chiral operators

$$O_{2,3} \quad : \quad O^{a,b}_{6\times\bar{6}} = \bar{q}_R T^a q_L \;\; \bar{q}_R T^b q_L \Big|_{6\times\bar{6}} \;\; \rightarrow \;\; g_{6\times\bar{6}} \, \frac{F_0^4}{8} \left[\mathrm{Tr}\left(T^a U T^b U\right) + \mathrm{Tr}\left(T^a U\right) \mathrm{Tr}\left(T^b U\right) \right]$$

$$O_{4,5} \quad : \quad O^{a,b}_{8\times 8} = \bar{q}_L T^a \gamma_\mu q_L \;\; \bar{q}_R T^b \gamma^\mu q_R \;\; \rightarrow \;\; g_{8\times 8} \, \frac{F_0^4}{4} \, \mathrm{Tr}\left(T^a U T^b U^\dagger\right) \,,$$

- Non-perturbative dynamics encoded in each low-energy constant

$$g_{6\otimes\bar{6}}, \;\; g_{8\otimes 8}$$

- for each chiral rep, each color contraction has its own LEC g
- ΔL=2 operators $T^a \quad \rightarrow \quad T^1 + iT^2$
- K–Kbar mixing ΔS=2 operators

$$T^a \quad \rightarrow \quad T^6 - iT^7$$

Matching quark operators onto chiral operators

$$O_{2,3} \quad : \quad O^{a,b}_{6\times\bar{6}} = \bar{q}_R T^a q_L \;\; \bar{q}_R T^b q_L \Big|_{6\times\bar{6}} \quad \to \quad g_{6\times\bar{6}} \, \frac{F_0^4}{8} \left[\mathrm{Tr}\left(T^a U T^b U\right) + \mathrm{Tr}\left(T^a U\right) \mathrm{Tr}\left(T^b U\right) \right]$$

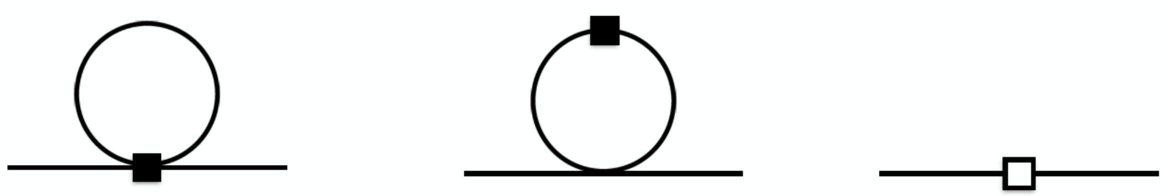
$$O_{4,5} \quad : \quad O^{a,b}_{8\times 8} = \bar{q}_L T^a \gamma_\mu q_L \;\; \bar{q}_R T^b \gamma^\mu q_R \quad \to \quad g_{8\times 8} \, \frac{F_0^4}{4} \, \mathrm{Tr}\left(T^a U T^b U^\dagger\right) \; ,$$

$$\mathcal{M}^{\pi\pi}_{6\times\bar{6}} \equiv \langle \pi^+ | O^{1+i2,1+i2}_{6\times\bar{6}} | \pi^- \rangle \quad = \quad \langle \bar{K}^0 | O^{6-i7,6-i7}_{6\times\bar{6}} | K^0 \rangle \equiv \mathcal{M}^{K\bar{K}}_{6\times\bar{6}}$$

$$\mathcal{M}^{\pi\pi}_{8\times 8} \equiv \langle \pi^+ | O^{1+i2,1+i2}_{8\times 8} | \pi^- \rangle \quad = \quad \langle \bar{K}^0 | O^{6-i7,6-i7}_{8\times 8} | K^0 \rangle \equiv \mathcal{M}^{K\bar{K}}_{8\times 8}$$

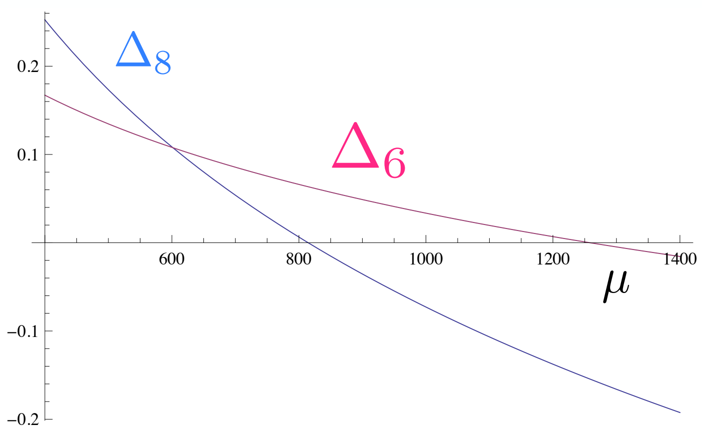
(LO in chiPT)

Quark masses (pion masses) break chiral symmetry. So previous relations modified at NLO. We did a loop computation to estimate the size of that splitting.



$$\mathcal{M}^{\pi\pi}_{8\times 8} = \mathcal{M}^{K\bar{K}}_{8\times 8} \times \frac{F_\pi^2}{F_K^2} \times (1+\Delta_{8\times 8}) = \mathcal{M}^{K\bar{K}}_{8\times 8} \times R_{8\times 8}$$

$$\mathcal{M}^{\pi\pi}_{6\times\bar{6}} = \mathcal{M}^{K\bar{K}}_{6\times\bar{6}} \times \frac{F_\pi^2}{F_K^2} \times (1+\Delta_{6\times\bar{6}}) = \mathcal{M}^{K\bar{K}}_{6\times\bar{6}} \times R_{6\times\bar{6}} \,,$$



$$\Delta_{8\times 8} = \frac{1}{(4\pi F_0)^2}\left[\frac{m_\pi^2}{4}(-4+5L_\pi) - m_K^2(-1+2L_K) + \frac{3}{4}m_\eta^2 L_\eta - a_{8\times 8}\left(m_K^2 - m_\pi^2\right)\right]$$

$$\Delta_{6\times\bar{6}} = \frac{1}{(4\pi F_0)^2}\left[-\frac{m_\pi^2}{4}(4-3L_\pi) - m_K^2(-1+2L_K) + \frac{5}{4}m_\eta^2 L_\eta - a_{6\times\bar{6}}\left(m_K^2 - m_\pi^2\right)\right]$$

$$\left(L_{\pi,K,\eta} \equiv \log \mu_\chi^2/m^2_{\pi,K,\eta}\right)$$

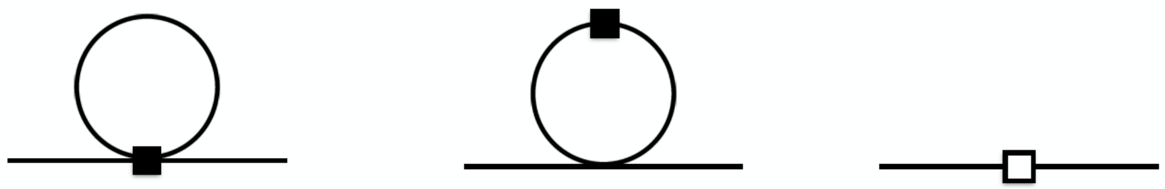
- We agree with loop corrections to K-Kbar (Becirevic, Villadoro, 2004)
- Counter-terms from NLO local operators have the form (V. Cirigliano, E. Golowich, 2000)

$$\delta^{K\bar{K}}_{8\times 8} = a_{8\times 8}\, m_K^2 + b_{8\times 8}\left(m_K^2 + \frac{1}{2}m_\pi^2\right)$$

$$\delta^{\pi\pi}_{8\times 8} = a_{8\times 8}\, m_\pi^2 + b_{8\times 8}\left(m_K^2 + \frac{1}{2}m_\pi^2\right)$$

- Low-energy coefficients {a} could be extracted (in principle) from K-Kbar mixing computed using lattice QCD at different values for the quark masses

Estimating central value and uncertainty



$$\mathcal{M}^{\pi\pi}_{8\times 8} = \mathcal{M}^{K\bar{K}}_{8\times 8} \times \frac{F_\pi^2}{F_K^2} \times (1+\Delta_{8\times 8}) = \mathcal{M}^{K\bar{K}}_{8\times 8} \times R_{8\times 8}$$

$$\mathcal{M}^{\pi\pi}_{6\times \bar{6}} = \mathcal{M}^{K\bar{K}}_{6\times \bar{6}} \times \frac{F_\pi^2}{F_K^2} \times (1+\Delta_{6\times \bar{6}}) = \mathcal{M}^{K\bar{K}}_{6\times \bar{6}} \times R_{6\times \bar{6}} \ ,$$

- For central value for Δ's, set renormalization scale to rho mass and counter-terms =0
- Adopted two prescriptions for estimating the error due to unknown $\delta^{K\bar{K}}_{8\times 8}, \delta^{\pi\pi}_{8\times 8}$
  - Naive-dimensional analysis : $|a_{8\times 8, 6\times \bar{6}}| \sim O(1)$

    gives $\Delta_{8\times 8} = 0.02(20), \ \Delta_{6\times \bar{6}} = 0.07(20)$
  - O(1) change in (log) renormalization scale (Manohar '96): $\Delta_n^{(\mathrm{ct})} = \pm |d\Delta_n^{(\mathrm{loops})}/d(\log \mu_\chi)|$

    gives $\Delta_{8\times 8} = 0.02(36), \ \Delta_{6\times \bar{6}} = 0.07(16)$
- For final analysis, chose $\Delta_{8\times 8} = 0.02(30)\ , \ \Delta_{6\times \bar{6}} = 0.07(20)$
  - This choice gives

$$R_{8\times 8} = 0.72(21) \ (\sim 30\% \text{ uncertainty})$$
$$R_{6\times \bar{6}} = 0.76(14) \ (\sim 20\% \text{ uncertainty})$$

Relate our operators to those defined by FLAG (Aoki et.al, 1607.00299)

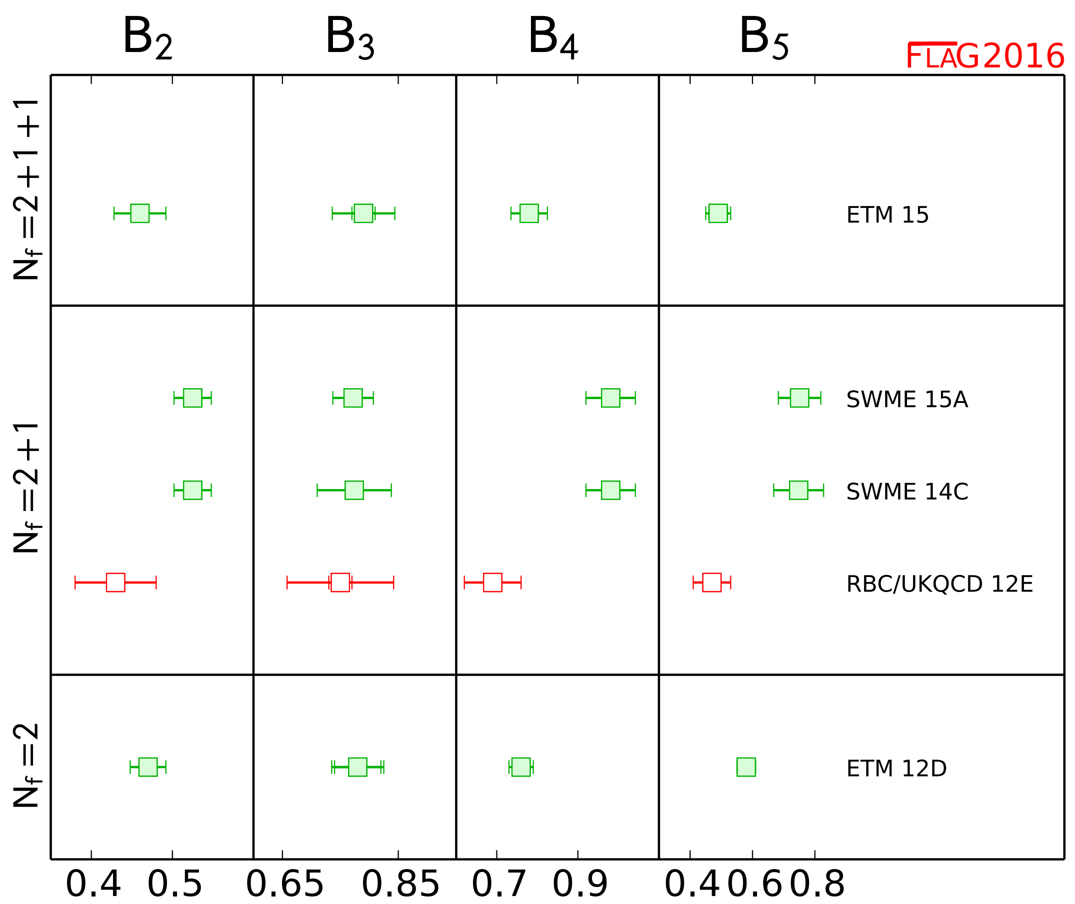
average central values for Nf=2+1 and Nf=2+1+1

$$\langle\pi^+|O_2|\pi^-\rangle = -\frac{5}{12}\,B_2\,K\times R_{6\times\bar{6}},\qquad K=\frac{2\,F_K^2\,m_K^4}{(m_d+m_s)^2}$$

$$\langle\pi^+|O_3|\pi^-\rangle = \frac{1}{12}\,B_3\,K\times R_{6\times\bar{6}}$$

$$\langle\pi^+|O_4|\pi^-\rangle = -\frac{1}{3}\,B_5\,K\times R_{8\times 8}$$

$$\langle\pi^+|O_5|\pi^-\rangle = -B_4\,K\times R_{8\times 8}$$



LQCD input: B_2, B_3: O(10%) error

B_4, B_5: O(20%) error

$$\langle\pi^+|O_1|\pi^-\rangle = (1.0\pm0.1\pm0.2)\times10^{-4}\ \mathrm{GeV}^4$$

$$\langle\pi^+|O_2|\pi^-\rangle = -(2.7\pm0.3\pm0.5)\times10^{-2}\ \mathrm{GeV}^4$$

$$\langle\pi^+|O_3|\pi^-\rangle = (0.9\pm0.1\pm0.2)\times10^{-2}\ \mathrm{GeV}^4$$

$$\langle\pi^+|O_4|\pi^-\rangle = -(2.6\pm0.8\pm0.8)\times10^{-2}\ \mathrm{GeV}^4$$

$$\langle\pi^+|O_5|\pi^-\rangle = -(11\pm2\pm3)\times10^{-2}\ \mathrm{GeV}^4$$

Fractional error:

O_2, O_3: O(20%) error

O_5 : O(40%) error

O_4 : O(35%) error

Updating M. Savage's (1999) determination of $\langle \pi^+ | O_1 | \pi^- \rangle$

Observation is that

$$O_1,\ O_{\Delta S=2},\ Q_2^{(27\otimes 1)} \in \mathbf{27}$$

$$K^+ \quad \rightarrow \quad \pi^+ \pi^0$$

$$Q_2^{(27\times 1)} \quad \rightarrow \quad g_{27\times 1}\ F_0^4\ \left(L_{\mu 32} L^{\mu}_{11} + \frac{2}{3} L_{\mu 31} L^{\mu}_{12} \right)$$

$$O_{\Delta S=2} \quad \rightarrow \quad \frac{5}{3}\, g_{27\times 1}\ F_0^4\ L_{\mu 32} L^{\mu}_{32}$$

$$4\, O_1 \quad \rightarrow \quad \frac{5}{3}\, g_{27\times 1}\ F_0^4\ L_{\mu 12} L^{\mu}_{12}$$

$$L^{\mu}_{ij} = i (U^{\dagger} \partial^{\mu} U)_{ij}$$

- Chiral loops and counter terms again give:

$$\begin{aligned}\langle\pi^+|O_1|\pi^-\rangle &= \frac{5}{3}\, g_{27\times 1}\; m_\pi^2 F_\pi^2 \left\{1+\frac{m_\pi^2}{(4\pi F_0)^2}(-1+3L_\pi)+\delta^{\pi\pi}_{27\times 1}\right\}\\ \langle\pi^+\pi^0|iQ_2|K^+\rangle &= \frac{5}{3}\, g_{27\times 1}\; F_\pi\;\left(m_K^2-m_\pi^2\right)\;\left\{1+\Delta_{27}^{K^+\pi^+\pi^0}\right\}\end{aligned}$$

- for ΔS=1 part, loops are small, and counter terms found to also be small at large Nc because of factorization of Q_2 into product of currents (Cirigliano, Ecker, Neufeld, Pich, 2004)
- lattice QCD computation of K-> pi pi O(10%) error (Blum et. al. 2015)

--> g_{27} =0.34(3)$_{\text{LQCD}}$(2)$_{\text{chiPT}}$

- with 20% error in $\delta^{\pi\pi}_{27\times 1}$ gives our estimate for O_1 :

$$\langle\pi^+|O_1|\pi^-\rangle = (1.0\pm 0.1\pm 0.2)\times 10^{-4}\ \text{GeV}^4$$

- As expected from general considerations, this matrix element is suppressed compared to other ΔL=2 two pion matrix elements

Comments on validity of chiral SU(3)

general comment: semi-leptonic K decay form factors agree well between lattice QCD and chiral SU(3), but need to check each example

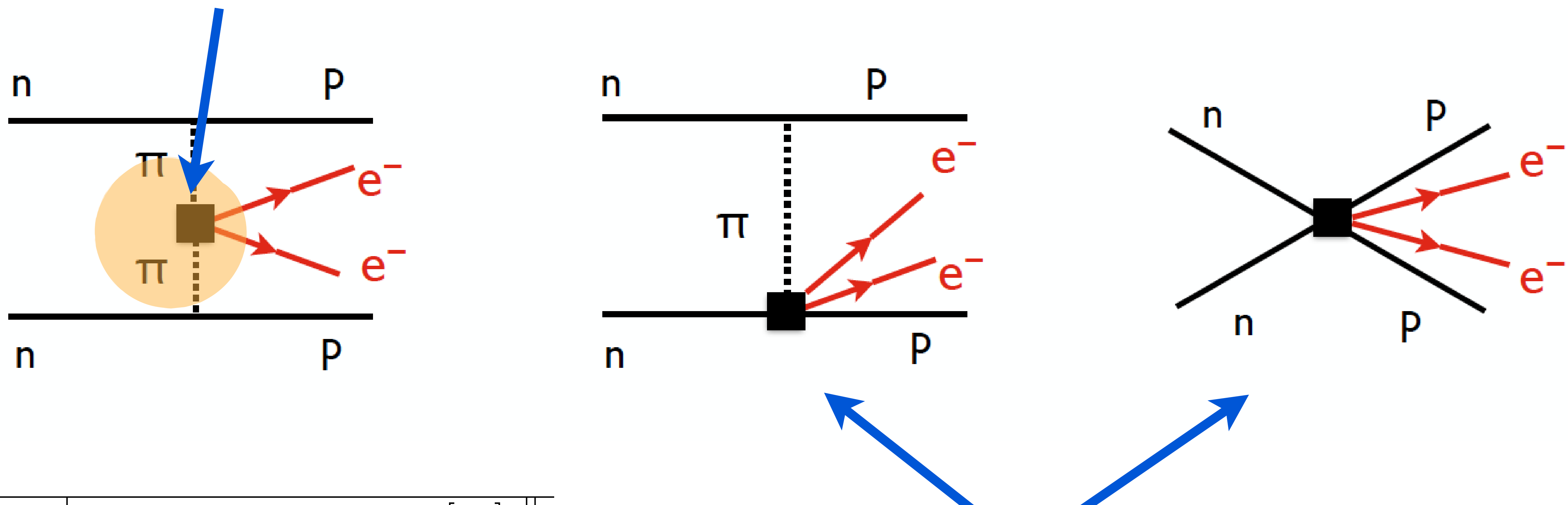
• loop factors small in our case O(30%)

• Our results for g_{8x8} using K-> pi pi decay instead of K-Kbar in reasonable agreement with method using K-Kbar

• Our value for g_{27} extracted using K-Kbar and K->pi pi agree in reasonable agreement

Summary

progress on these interactions from
LQCD and chiral PT



$g_{27\times1}$	0.38 ± 0.08	[33]
$g_{8\times8}$	$-(3.1 \pm 1.3)\ \mathrm{GeV}^2$	[33]
$g^{\mathrm{mix}}_{8\times8}$	$-(11 \pm 4)\ \mathrm{GeV}^2$	[33]

progress on these interactions from
LQCD just beginning

two pion matrix element results consistent with chiral PT expectations and naive dimensional analysis

New dimension-9 $\Delta L=2$ LNV physics potentially accessibly at LHC or future hadron collider

Complementarity between 0nubb and hadron colliders

(see Michael Ramsey-Musolf's talk)

But is this generic?

Not necessarily.....

Dimension 7 ΔL=2 LNV operators

Lehman '14
V. Cirigliano, W. Dekens, J. de Vries, MG, E. Mereghetti, (1707/08.zzzz) Preliminary!

Class 1	$\psi^2 H^4$
$\mathcal{O}_{LH}$	$\epsilon_{ij}\epsilon_{mn}(L_i^T C L_m)H_j H_n (H^\dagger H)$

Class 5	$\psi^4 D$
$\mathcal{O}^{(1)}_{LL\bar{d}uD}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(L_i^T C (D^\mu L)_j)$

Class 2	$\psi^2 H^2 D^2$
$\mathcal{O}^{(1)}_{LHD}$	$\epsilon_{ij}\epsilon_{mn}(L_i^T C (D_\mu L)_j)H_m (D^\mu H)_n$
$\mathcal{O}^{(2)}_{LHD}$	$\epsilon_{im}\epsilon_{jn}(L_i^T C (D_\mu L)_j)H_m (D^\mu H)_n$
Class 3	$\psi^2 H^3 D$
$\mathcal{O}_{LHDe}$	$\epsilon_{ij}\epsilon_{mn}(L_i^T C \gamma_\mu e)H_j H_m (D^\mu H)_n$
Class 4	$\psi^2 H^2 X$
$\mathcal{O}_{LHB}$	$\epsilon_{ij}\epsilon_{mn} g'(L_i^T C \sigma^{\mu\nu} L_m)H_j H_n B_{\mu\nu}$
$\mathcal{O}_{LHW}$	$\epsilon_{ij}(\epsilon\tau^I)_{mn} g(L_i^T C \sigma^{\mu\nu} L_m)H_j H_n W^I_{\mu\nu}$

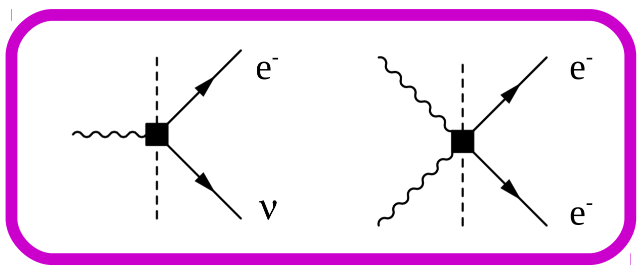
Class 6	$\psi^4 H$
$\mathcal{O}_{LL\bar{e}H}$	$\epsilon_{ij}\epsilon_{mn}(\bar{e}L_i)(L_j^T C L_m)H_n$
$\mathcal{O}^{(1)}_{LLQ\bar{d}H}$	$\epsilon_{ij}\epsilon_{mn}(\bar{d}L_i)(Q_j^T C L_m)H_n$
$\mathcal{O}^{(2)}_{LLQ\bar{d}H}$	$\epsilon_{im}\epsilon_{jn}(\bar{d}L_i)(Q_j^T C L_m)H_n$
$\mathcal{O}_{LL\bar{Q}uH}$	$\epsilon_{ij}(\bar{Q}_m u)(L_m^T C L_i)H_j$
$\mathcal{O}_{Leu\bar{d}H}$	$\epsilon_{ij}(L_i^T C \gamma_\mu e)(\bar{d}\gamma^\mu u)H_j$

12 independent operators

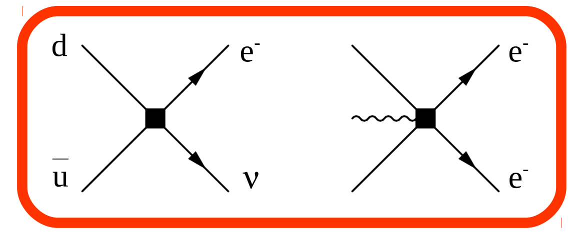
- special cases: i) class 1 modifies Weinberg operator scale > 1200 TeV
  ii) purely leptonic operators contribute to neutrino mass (at one-loop) and neutrino magnetic moment (at tree-level)
- operators involving quarks contribute to 0nubb

Dimension 7 ΔL=2 LNV operators

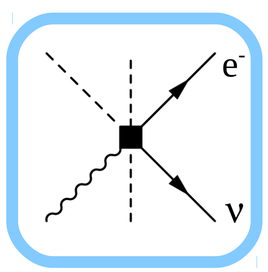
Nice figures from E. Mereghetti, INT seminar 2017



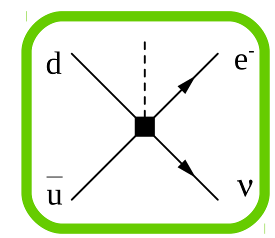
$$\varepsilon_{ij}\varepsilon_{mn}\, L_i^T C (D_\mu L)_j\, H_m (D^\mu H)_n$$



$$\varepsilon_{ij}\, \bar{d}\gamma_\mu u\, L_i^T C (D^\mu L)_j$$

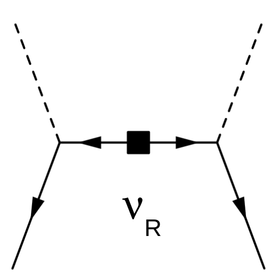


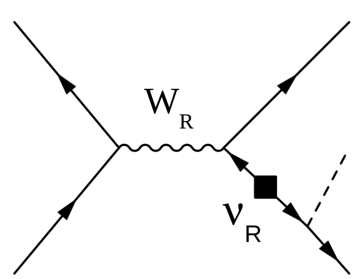
$$\varepsilon_{ij}\varepsilon_{mn}\, L_i^T C\gamma_\mu e\, H_j H_m (D^\mu H)_n$$

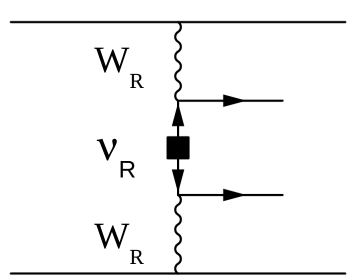


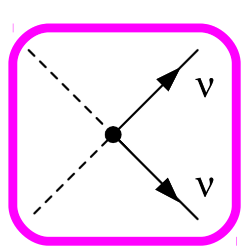
$$\varepsilon_{ij}\varepsilon_{mn} \bar{d} L_i\, Q_j^T C L_m\, H_n$$

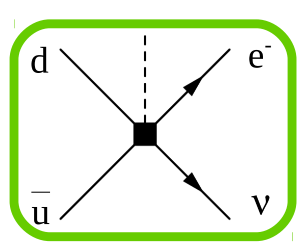
Sample dimension -5,-7,-9 ΔL=2 LNV operators

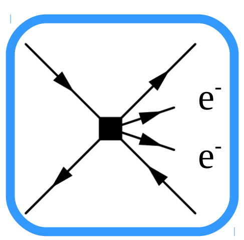












Dimension 7 $\Delta L=2$ LNV operators:
neutrino masses, neutrino magnetic moment

- purely leptonic operators contribute to neutrino mass (one-loop) ("bound" by requiring new contribution to neutrino mass < 1 eV)

(only those more constraining than 0nubb shown)

$$\mathcal{C}^{(1)}_{LHD}: \quad \Lambda > 280\,\text{TeV}, \quad \mathcal{C}^{(2)}_{LHD}: \quad \Lambda > 350\,\text{TeV},$$
$$C_{LHW}: \quad \Lambda > 460\,\text{TeV}$$

- neutrino magnetic moment (at tree-level) constrained by solar neutrino experiments (Borexino)

(Canas, Miranda, Parada, Tortola, Valle, '16)

$$|\mathcal{C}_{LHB} - \mathcal{C}_{LHW}| \lesssim \frac{1}{4 m_e v^2} 10^{-10} \to \Lambda > 11\,\text{TeV}\,.$$

Dimension 7 $\Delta L=2$ LNV quark operators:
QCD running to Electroweak scale

- running either trivial (operators with no quarks, or those with vector or axial currents) or given scalar or tensor:

$\mathcal{O}_{LL\bar{Q}uH}$ scalar

$\mathcal{O}^{(1,2)}_{LLQ\bar{d}H}$ combination of scalar and tensor

$$\frac{d}{d\ln\mu}\mathcal{C}_{LL\bar{Q}uH} = -6C_F\,\frac{\alpha_s}{4\pi}\mathcal{C}_{LL\bar{Q}uH}\,, \quad \frac{d}{d\ln\mu}C_S^{(1,2),ij} = -6C_F\,\frac{\alpha_s}{4\pi}C_S^{(1,2),ij}$$

$$\frac{d}{d\ln\mu}C_T^{(1,2),ij} = 2C_F\,\frac{\alpha_s}{4\pi}C_T^{(1,2),ij}\,,$$

Dimension 7 $\Delta L=2$ LNV operators:

Integrate out W, H at electroweak scale, generate dim-6, -7, -9 operators

$$\mathcal{L}_{\Delta L=2} = -\frac{1}{2}(m_\nu)_{ij}\nu^t_{L,\,i}\,C\nu_{L,\,j} + \mu_{ij}\,\nu^{t\,j}\,C\sigma^{\mu\nu}\nu^i\,eF_{\mu\nu} + \mathcal{L}^{(6)}_{\Delta L=2} + \mathcal{L}^{(7)}_{\Delta L=2} + \mathcal{L}^{(9)}_{\Delta L=2}.$$

ld

ld

sd

$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}}\Big\{C^{(6)}_{\mathrm{VL},ij}\,\bar{u}_L\gamma^\mu d_L\,\bar{e}_{R,i}\,\gamma_\mu\,C\bar{\nu}^t_{L,j} + C^{(6)}_{\mathrm{VR},ij}\,\bar{u}_R\gamma^\mu d_R\,\bar{e}_{R,i}\,\gamma_\mu\,C\bar{\nu}^t_{L,j}$$
$$+C^{(6)}_{\mathrm{SR},ij}\,\bar{u}_L d_R\,\bar{e}_{L,i}\,C\bar{\nu}^t_{L,j} + C^{(6)}_{\mathrm{SL},ij}\,\bar{u}_R d_L\,\bar{e}_{L,i}\,C\bar{\nu}^t_{L,j} + C^{(6)}_{\mathrm{T},ij}\,\bar{u}_L\sigma^{\mu\nu}d_R\,\bar{e}_{L,i}\sigma_{\mu\nu}\,C\bar{\nu}^t_{L,j}\Big\} + \mathrm{h.c.}$$

$$\mathcal{L}^{(7)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}v}\Big\{C^{(7)}_{\mathrm{VL},ij}\,\bar{u}_L\gamma^\mu d_L\,\bar{e}_{L,i}\,C\,i\overleftrightarrow{\partial}_\mu\bar{\nu}^t_{L,j} + C^{(7)}_{\mathrm{VR},ij}\,\bar{u}_R\gamma^\mu d_R\,\bar{e}_{L,i}\,C i\overleftrightarrow{\partial}_\mu\bar{\nu}^t_{L,j}\Big\} + \mathrm{h.c.}$$

$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{\bar{e}_{L,i}C\bar{e}^t_{L,j}}{v^5}\Big\{C^{(9)}_{1,ij}\,\bar{u}_L\gamma^\mu d_L\,\bar{u}_L\gamma_\mu d_L + C^{(9)}_{4,ij}\,\bar{u}_L\gamma^\mu d_L\,\bar{u}_R\gamma_\mu d_R + C^{(9)}_{5,ij}\,\bar{u}^\alpha_L\gamma^\mu d^\beta_L\,\bar{u}^\beta_R\gamma_\mu d^\alpha_R\Big\}$$

Dimension 7 ΔL=2 LNV operators:
QCD running below electroweak scale

$$\frac{d}{d\ln\mu}C^{(6)}_{\mathrm{SL\,(SR)}} = -6C_F\,\frac{\alpha_s}{4\pi}C^{(6)}_{\mathrm{SL\,(SR)}}\,,\quad \frac{d}{d\ln\mu}C^{(6)}_{\mathrm{T}} = 2C_F\,\frac{\alpha_s}{4\pi}C^{(6)}_{\mathrm{T}}\,.$$

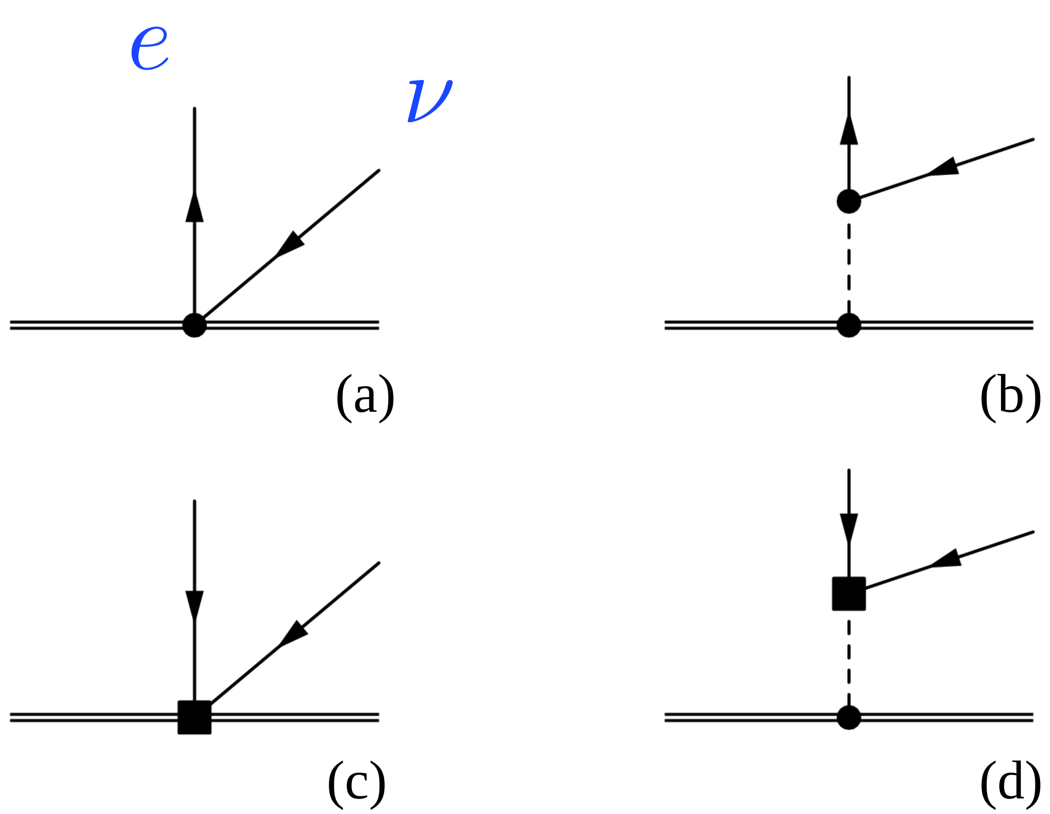
$$\frac{d}{d\ln\mu}C^{(9)}_{1} = 6\left(1-\frac{1}{N_c}\right)\frac{\alpha_s}{4\pi}C^{(9)}_{1}\,,$$

$$\frac{d}{d\ln\mu}\begin{pmatrix}C^{(9)}_{4}\\ C^{(9)}_{5}\end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix}6/N_c & 0\\ -6 & -12C_F\end{pmatrix}\begin{pmatrix}C^{(9)}_{4}\\ C^{(9)}_{5}\end{pmatrix}$$

Dimension 7 $\Delta L=2$ LNV operators

Long-distance contributions : single nucleon couplings

use SU(2) chiral EFT and external source method



SM

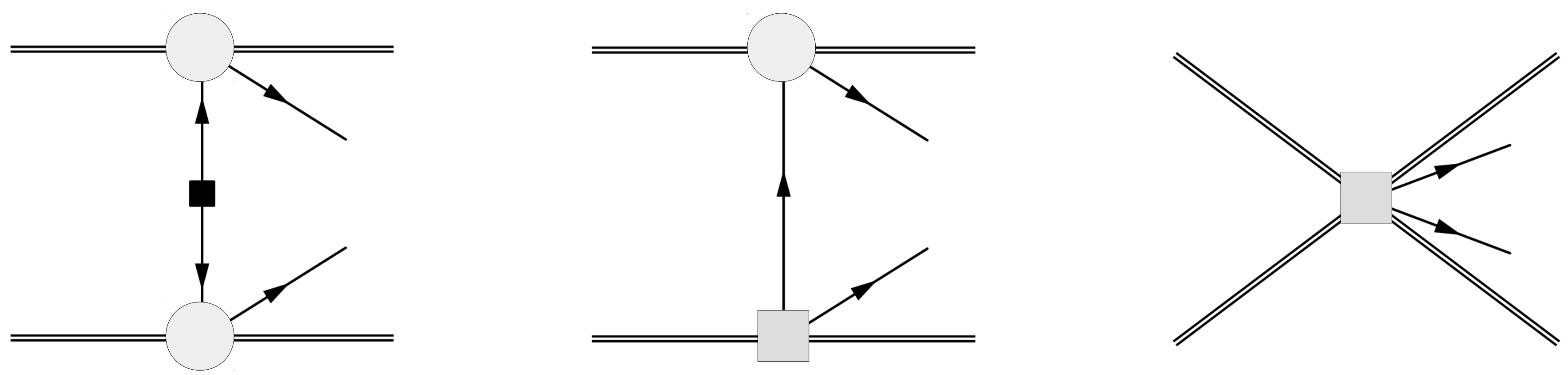
dim-6, dim-7

long-distance 0nubb = top row ^2 (SM)

\+ top row * bottom row

Dimension 7 ΔL=2 LNV operators:

Long-distance and short-distance contributions



total 0nubb contribution = SM

+ long-distance neutrino (middle) + short distance (right)

"known" LEC inputs (right)
+ some NLO ops fixed by
reparameterization invariance

$g_{27\times1}$	0.38 ± 0.08	[33]	g_A	1.272 ± 0.002	[34]
$g_{8\times8}$	$-(3.1 \pm 1.3)\ \text{GeV}^2$	[33]	g_S	0.97 ± 0.13	[35]
$g_{8\times8}^{\text{mix}}$	$-(11 \pm 4)\ \text{GeV}^2$	[33]	g_T	0.99 ± 0.06	[35]

LD: 1 unknown LEC:

$$g_T' \quad \sim O(1)$$

SD: 2 unknown LECs:

$$g_{27\times1}^{\pi N},\ g_{27\times1}^{NN} \quad \sim O(1)$$

Dimension 7 ΔL=2 LNV operators:

Matrix elements and general formula

Fortunately, 15 matrix elements needed for computing rate have been computed by several groups, using different methods

Muto, Bender and Klapdor, 1989
Barea and Iachello, 2009
Hyvarinen and Suhonen, 2015
Horoi and Neacsu, 2016, 2017

$$\left(T^{0\nu}_{1/2}\right)^{-1} = g_A^4\Big\{G_{01}\,|\mathcal{M}_{\rm SM}|^2 + 4G_{02}\,|\mathcal{M}_E|^2 + 2G_{04}\left[|\mathcal{M}_{m_e}|^2 + {\rm Re}\left(\mathcal{M}^*_{m_e}\mathcal{M}_{\rm SM}\right)\right] + G_{09}\,|\mathcal{M}_M|^2$$
$$-2G_{03}\,{\rm Re}\left(\mathcal{M}_{\rm SM}\mathcal{M}^*_E + 2\mathcal{M}_{m_e}\mathcal{M}^*_E\right) + G_{06}\,{\rm Re}\left(\mathcal{M}_{\rm SM}\mathcal{M}^*_M\right)\Big\}\,, \qquad (43)$$

$$G_{0k} = \frac{1}{\ln 2}\frac{G_F^4 m_e^2}{64\pi^5 R_A^2}\int dE_1 dE_2 |\mathbf{k}_1||\mathbf{k}_2| d\cos\theta\, b_{0k}\, F(Z,E_1)F(Z,E_2)\delta(E_1+E_2+M_f-M_i).$$

Dimension 7 ΔL=2 LNV operators:

Bounds on operators from 0nubb experiments

Bounds on:

effective dim-6, dim-7, dim-9 couplings (right)

Λ	^{76}Ge	^{82}Se	^{130}Te	^{136}Xe
$m_{\beta\beta}$ (eV)	0.19	1.4	0.49	0.1
Λ (TeV)				
$C^6_{\rm SL}$	210.	110.	150.	260.
$C^6_{\rm SR}$	210.	110.	150.	260.
C^6_T	180.	92.	140.	240.
$C^6_{\rm VL}$	150.	74.	110.	190.
$C^6_{\rm VR}$	26.	15.	20.	34.
$C^7_{\rm VL}$	6.4	3.3	4.6	7.8
$C^7_{\rm VR}$	6.4	3.3	4.6	7.8
C^9_1	14.	7.4	11.	19.
C^9_4	41.	21.	31.	53.
C^9_5	63.	32.	47.	81.

	^{76}Ge	^{82}Se	^{130}Te	^{136}Xe
$m_{\beta\beta}$ (eV)	0.17	1.6	0.32	0.084
Λ (TeV)				
$C^6_{\rm SL}$	270.	130.	220.	350.
$C^6_{\rm SR}$	270.	130.	220.	350.
C^6_T	220.	100.	180.	280.
$C^6_{\rm VL}$	180.	83.	150.	220.
$C^6_{\rm VR}$	33.	17.	28.	44.
$C^7_{\rm VL}$	8.1	3.8	6.8	11.
$C^7_{\rm VR}$	8.1	3.8	6.8	11.
C^9_1	13.	5.9	12.	18.
C^9_4	54.	26.	48.	69.
C^9_5	84.	40.	73.	110.

* bounds weaker or stronger depending on whether contribution is chirally suppressed or enhanced by large magnetic moment

Bounds more or less consistent with chiral expectations:

	SM	$C^{(6)}_{\rm SL,\,SR}$	$C^{(6)}_{\rm T}$	$C^{(6)}_{\rm VL}$	$C^{(6)}_{\rm VR}$	$C^{(7)}_{\rm VL,\,VR}$	$C^{(9)}_1$	$C^{(9)}_{4,5}$
$m_e\mathcal{M}_{\rm SM}$	$m_{\beta\beta}$	Λ_χ	$\Lambda_\chi\epsilon_\chi^2$	–	–	$\frac{\Lambda_\chi^2}{v}\,\epsilon_\chi^2$	$\frac{\Lambda_\chi^2}{v}\,\epsilon_\chi^2$	$\frac{\Lambda_\chi^2}{v}$
$m_e\mathcal{M}_M$	–	–	–	$\Lambda_\chi\epsilon_\chi^2$	–	–	–	–
$m_e\mathcal{M}_E$	–	–	–	$\Lambda_\chi\epsilon_\chi^3$	$\Lambda_\chi\epsilon_\chi^3$	–	–	–
$m_e\mathcal{M}_{me}$	–	–	–	$\Lambda_\chi\epsilon_\chi^3$	$\Lambda_\chi\epsilon_\chi^3$	–	–	–

Table 4: Power-counting estimates of the contribution of low-energy dimension-six, -seven and -nine operators to the matrix elements in Eq. (42). Here $\epsilon_\chi \equiv m_\pi/\Lambda_\chi$, where $\Lambda_\chi \sim m_N \sim 1$ GeV is the symmetry-breaking scale. For the power counting, we consider the electron energies and mass to be small, $E_1 \sim E_2 \sim m_e \sim \Lambda_\chi\,\epsilon_\chi^3$.

Dimension 7 ΔL=2 LNV operators:
Bounds on operators from 0nubb experiments

Bounds on:

effective dim-6, dim-7, dim-9 couplings (right)

electro-weak inv. dim-7 couplings (below):

Λ	^{76}Ge	^{82}Se	^{130}Te	^{136}Xe
$m_{\beta\beta}$ (eV)	0.19	1.4	0.49	0.1
Λ (TeV)				
$C^6_{\rm SL}$	210.	110.	150.	260.
$C^6_{\rm SR}$	210.	110.	150.	260.
C^6_T	180.	92.	140.	240.
$C^6_{\rm VL}$	150.	74.	110.	190.
$C^6_{\rm VR}$	26.	15.	20.	34.
$C^7_{\rm VL}$	6.4	3.3	4.6	7.8
$C^7_{\rm VR}$	6.4	3.3	4.6	7.8
C^9_1	14.	7.4	11.	19.
C^9_4	41.	21.	31.	53.
C^9_5	63.	32.	47.	81.

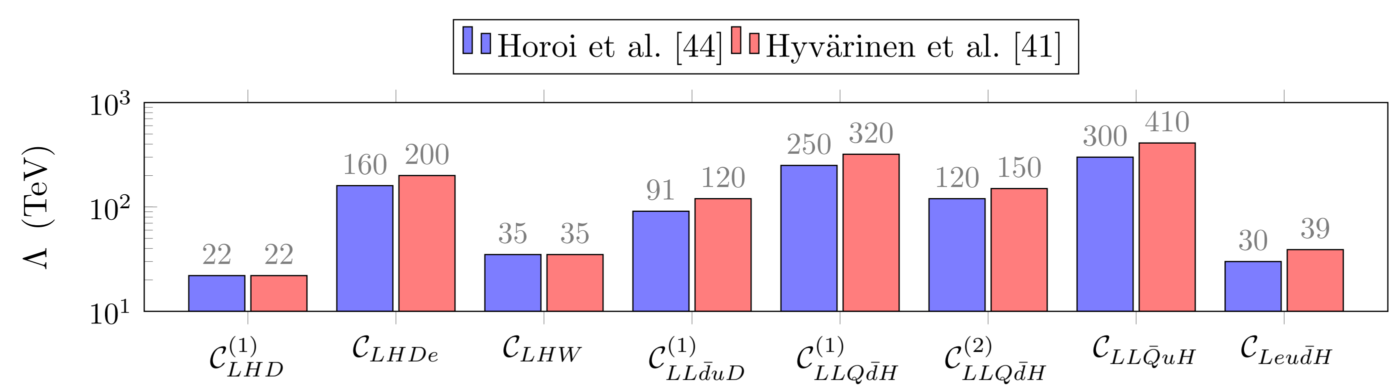
Λ	^{76}Ge	^{82}Se	^{130}Te	^{136}Xe
$m_{\beta\beta}$ (eV)	0.17	1.6	0.32	0.084
Λ (TeV)				
$C^6_{\rm SL}$	270.	130.	220.	350.
$C^6_{\rm SR}$	270.	130.	220.	350.
C^6_T	220.	100.	180.	280.
$C^6_{\rm VL}$	180.	83.	150.	220.
$C^6_{\rm VR}$	33.	17.	28.	44.
$C^7_{\rm VL}$	8.1	3.8	6.8	11.
$C^7_{\rm VR}$	8.1	3.8	6.8	11.
C^9_1	13.	5.9	12.	18.
C^9_4	54.	26.	48.	69.
C^9_5	84.	40.	73.	110.

* bounds weaker or stronger depending on whether contribution is chirally suppressed or enhanced by large magnetic moment

Λ	^{76}Ge	^{82}Se	^{130}Te	^{136}Xe
$\mathcal{C}^{(1)}_{\rm LHD}$	17.	8.7	13.	22.
$\mathcal{C}_{\rm LHDe}$	130.	65.	98.	160.
$\mathcal{C}_{\rm LHW}$	27.	14.	21.	35.
$\mathcal{C}^{(1)}_{\rm LLduD}$	70.	36.	53.	91.
$\mathcal{C}^{(1)}_{\rm LLQdH}$	200.	100.	140.	250.
$\mathcal{C}^{(2)}_{\rm LLQdH}$	93.	48.	72.	120.
$\mathcal{C}_{\rm LLQuH}$	250.	130.	180.	300.
$\mathcal{C}_{\rm LeudH}$	23.	14.	18.	30.

Λ	^{76}Ge	^{82}Se	^{130}Te	^{136}Xe
$\mathcal{C}^{(1)\rm S}_{\rm LHD}$	15.	7.2	15.	22.
$\mathcal{C}_{\rm LHDe}$	160.	73.	130.	200.
$\mathcal{C}_{\rm LHW}$	24.	11.	23.	35.
$\mathcal{C}^{(1)\rm S}_{\rm LLduD}$	94.	44.	82.	120.
$\mathcal{C}^{(1)\rm S}_{\rm LLQdH}$	240.	110.	210.	320.
$\mathcal{C}^{(2)\rm S}_{\rm LLQdH}$	110.	53.	94.	150.
$\mathcal{C}_{\rm LLQuH}$	310.	150.	260.	410.
$\mathcal{C}_{\rm LeudH}$	29.	15.	25.	39.

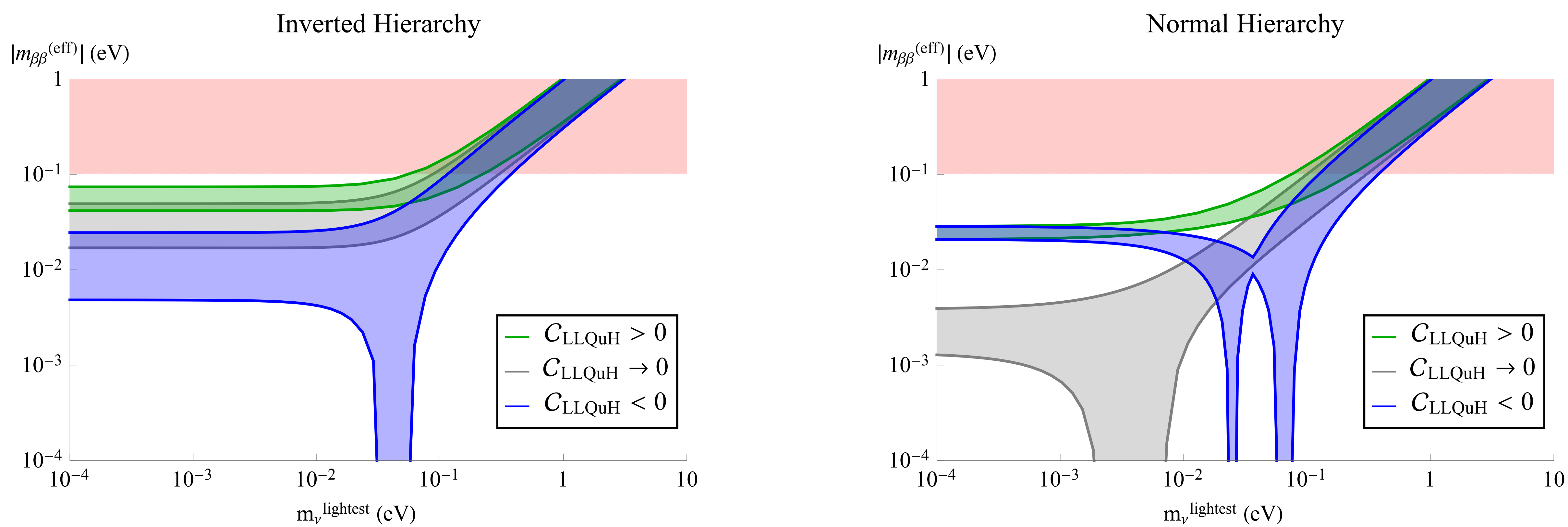
Single-coupling bounds* on dim-7 couplings from 0nubb (Kamland-Zen)



* constraints on C_LHD, C_LHW from neutrino mass much stronger

Dimension 7 $\Delta L=2$ LNV operators:

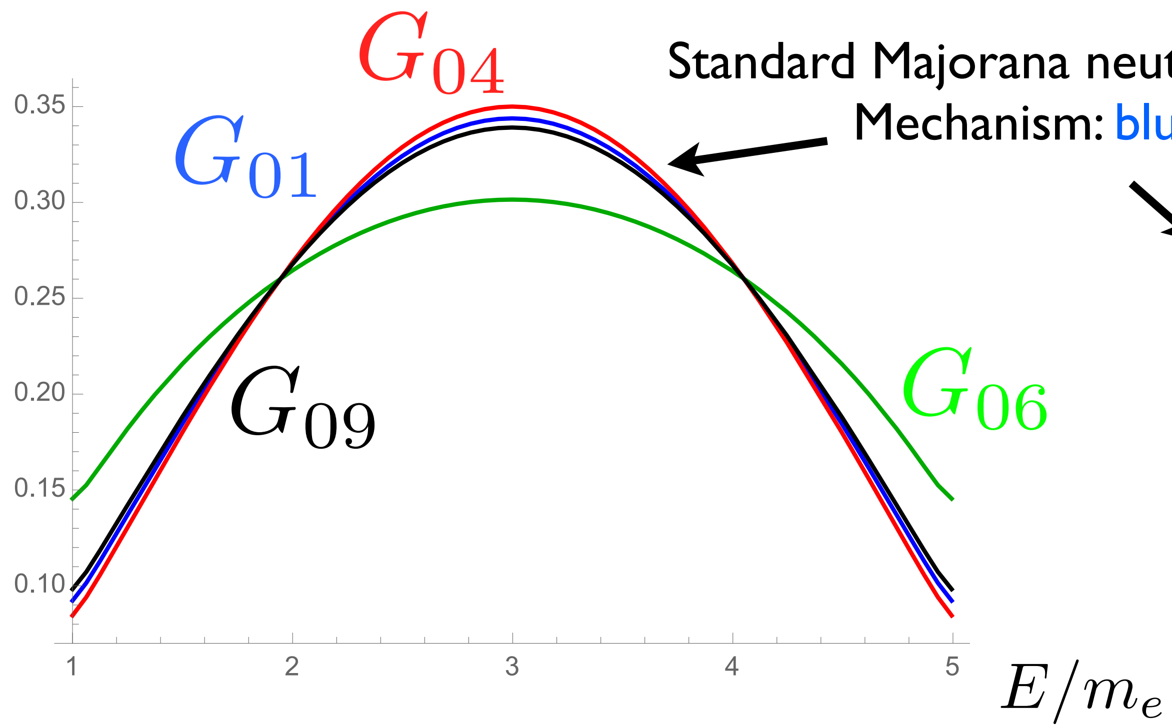
Simultaneous contributions of neutrino masses and dim-7 operators: m_eff

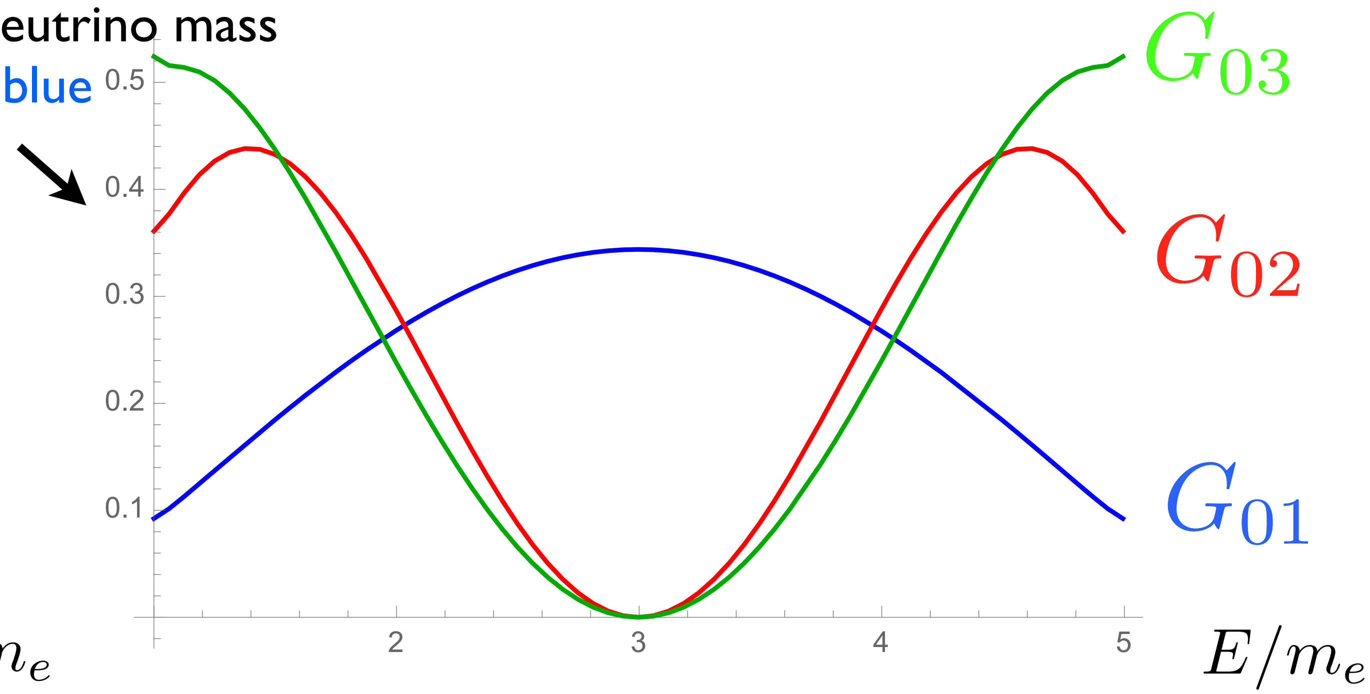


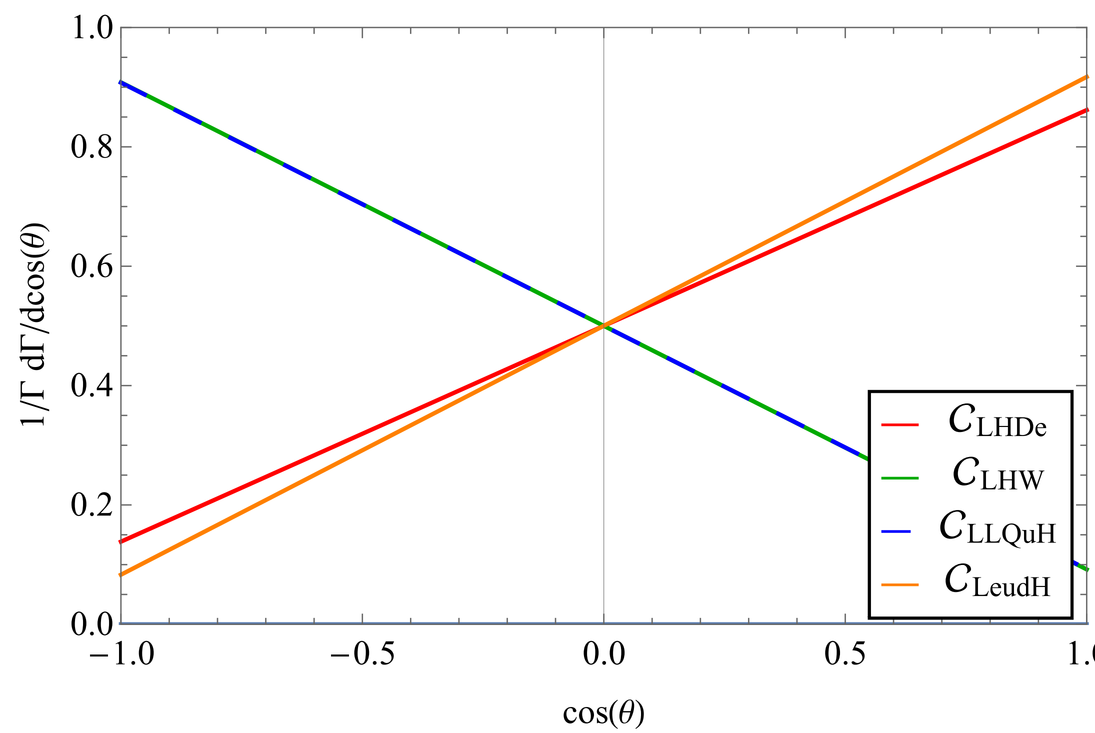
- Regions correspond to varying phases in dim-7 operator and PMNS matrix
- Size of region set by size of dim=7 operator (plots for 600 TeV)

Dimension 7 ΔL=2 LNV operators:

Simultaneous contributions of neutrino masses and dim-7 operators: energy and angular dependence







Summary

- New sources of $\Delta L=2$ LNV could dominate "standard non-standard" contribution (i.e., long-distance Majorana neutrino mass contribution)
- If neutrino hierarchy is "normal"*, such non-conventional sources for $\Delta L=2$ LNV and 0nubb only physics case for discovery
- Discussed possibilities, from both model-dependent and effective field theory descriptions. In contact limit reduced set of electroweak invariant operators: dim-7 and dim-9 operators.
- first chiral estimates of *all* two pion matrix elements arising from scalar 4-quark operators, necessary ingredient for leading 0nubb matrix elements arising from such non-conventional short-distance sources
- expect error to be improved only through direct LQCD computations. QCD input increasingly becoming under control for end-to-end computation. Lattice input for πNN and NNNN still needs to be developed (hard).
- dimension-7 $\Delta L=2$ LNV operators constrained by 0nubb to be O(100 TeV) scale. Probably not accessible at LHC, but future 100 TeV collider possible opportunity
- big inverse problem if $\Delta L=2$ LNV discovered, but that is a good situation to be in

*and outside of the quasi-degenerate region